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Development of a multi-frequency dielectric sensing system for real-time hay and forage moisture measurement

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**Development of a multi-frequency dielectric sensing system for
real-time hay and forage moisture measurement**

by

Ryan Carl Benning

A thesis submitted to the graduate faculty
In partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Agricultural Engineering (Agricultural Power and Machinery)

Program of Study Committee:
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Signatures have been redacted for privacy

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ABSTRACT

A previous study at Iowa State University has shown promise for the determination of hay and forage moisture content prior to compaction using multi-frequency dielectric measurements. This previous study used a sensing system to take sequential frequency measurements which takes considerable time. Due to the fast material flow through equipment, the measurements need to be taken in a very short time period. Taking multi-frequency dielectric measurements “simultaneously” will ensure all frequencies measurements are from the same sample mass.

This study has shown 1 MHz, 3 MHz, 7 MHz, and 13 MHz frequencies extracted from a multi-frequency signal are capable of providing the same signal information as sequentially scanned frequencies in milliseconds rather than multiple seconds. Hay bale moisture sensing was performed at Stardell Farms in Fredericksburg, Iowa, and the University of Wisconsin Arlington Research Station in Arlington, Wisconsin. Sensor plates were insulated and contained a guard plate around and behind them. Stardell Farms had the sensor plates 49.6 cm apart on a table top and Arlington had the sensor plates 36.8 cm apart in a fabricated bale chamber. Density independent moisture predictions were considerably better at Arlington with an adjusted R^2 equal to 0.80 and RMSE equal to 1.0 %MC wet basis for best sequential frequency combination 3 and 13 MHz. Arlington’s density independent moisture prediction has an adjusted R^2 equal to 0.79 and RMSE equal to 1.0 %MC wet basis for best extracted frequency combination of 3, 7, and 13 MHz. Stardell Farms yielded a density independent adjusted $R^2 = 0.68$ with 7.4 %MC wet basis for best frequency

combination of 7 MHz. The best extracted frequency combination of 3, 7, and 13 MHz yielded an adjusted R^2 equal to 0.67 with 7.5 %MC wet basis. At both locations the adjusted R^2 and RMSE was slightly higher for the sequential frequency combinations. At Stardell Farms the adjusted R^2 increased as the density increased while the adjusted R^2 remained approximately the same at Arlington regardless of density.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Hay and forage moisture content affects the harvesting, storing, buying, and selling of it (Eubanks and Birrell, 2001). Hay and forage is marketed on a wet weight basis making it advantageous to harvest in the optimal moisture range. When hay is harvested too dry more leaves fall off making it less desirable. Also, producers will have a lighter product yielding lower profits. Spoilage and possibly internal combustion can occur with hay after being harvested too wet.

To successfully harvest and store wet hay, a preservative needs to be added during harvest. Unfortunately, hay preservatives are relatively expensive so they are not economical for everyday use. However, impending weather conditions may make the use of hay preservatives more profitable than allowing the hay to be rained on. Knowing the moisture content during harvest allows for variable rate application of hay preservatives. This saves the producer money by only applying the appropriate amount of preservative during harvest.

Field maps made with a global positioning system providing spatial yield and moisture information present the producer with an opportunity to make decisions that optimize profits. Various attempts have been made to sense mass flow and moisture content which are needed to make yield maps. Some of the mass flow attempts have included continuous weighing of the forage wagons or bales, impact plates, feed roll displacement, capacitance sensors, PTO shaft torque, and attenuation (Marcotte, 1999). Research performed in developing moisture sensors include methods involving electric meters; acoustics; near infrared reflectance (NIR) and dielectric measurements in the microwave, radio wave, and low frequency ranges (Henson et al., 1987; Luz and To, 2001; Hooper, 1980; Nelson, 1999; Eubanks and Birrell, 2001).

Literature Review

Predicting mass flow and material moisture of forages is challenging due to the high mass flow rates of forage material through the machine. The moisture content of hay and forage varies considerably from cutting to harvest with material being handled a multitude of times (Shinners et al., 2003). If the material flow is constantly changing this also makes predicting moisture content and the application of hay preservatives difficult.

The most common hay preservative used to reduce storage losses is propionic acid. Propionic acid has been found to reduce microbial growth, bale heating, and protein damage (Shinners, 2000). This was determined by applying 0.8 percent propionic acid to hay greater than 25 percent moisture content wet basis (% MC wet basis). The key to maintaining bale quality and keeping dry matter loss below 4% was baling at moisture contents below 16 percent moisture content wet basis (%MC wet basis) for large square bales. Dry matter loss and reductions in hay quality were related to initial bale moisture content (Buckmaster and Heinrichs, 1993; Shinners, 2000).

Another approach to harvesting wet bales is drying them after harvest. In the event that wet bales need to be made, a drying system could be utilized to dry bales to the correct moisture content. The problem with this method is that equilibrium bale moisture contents are in the 3-10 percent moisture range (Descoteaux, 2002). After the drying front goes through the entire bale the first few layers become over dried. Most commercial hay producers try to maintain moisture contents above 12 percent since hay is sold on a wet weight basis and over drying results in a loss of income.

With so many variables to consider for harvesting hay and forage the need for a real-time moisture sensor becomes apparent. Knowing the moisture content allows the producer to make a more educated decision which should increase profits. The moisture content can answer questions about whether propionic acid is required and its application rate to minimize storage losses based on predicted storage times and harvesting quality.

Moisture sensing systems have a strong presence in the grain industry because grain sales are moisture and weight dependent. Grain moisture sensors using capacitive type methods and other dielectric measurements have been in widespread commercial use for a number of years. The dielectric properties of several grains are specified in ASAE Standard D293.2 (ASAE, 1998). Measured impedance depends on both the moisture content and the bulk density of the sample. Many of these moisture sensors require field calibrations to account for the changes in sample density. The development of density-independent functions of the dielectric properties of grains has been and still is being investigated in both the radio and microwave frequency ranges. The baseline for hay moisture measurement comparisons is oven drying using ASAE Standard S358.2 (ASAE, 2003). This standard requires a representative sample to be in the oven for 24 hours at 103 degrees Celsius or for 72 hours at 60 degrees Celsius.

Henson et al. (1987) compared many commercially available hay and forage moisture sensor meters to standard oven drying measurement methods. The Delmhorst meter employed direct current and estimated forage moisture content with a Pearson's coefficient, R^2 , equal to 0.85 with a standard error of 3.47 % MC wet basis. The Froment meter used alternating current operating at 5 MHz (Henson et al., 1987). The Froment meter yielded an R^2 of 0.74 and a standard error of 5.59 % MC wet basis. A microwave meter operating at 10 GHz yielded an R^2 of 0.80 and a standard error of 4.06 % MC wet basis (Henson et al., 1987). Another commercially available forage moisture meter is the Dickey John Forage Moisture tester based on measuring electrical capacitance (Dickey John, 1981). When averaging four alfalfa readings this meter has an R^2 of 0.85 and a 4.8 %MC wet basis coefficient of variation. The coefficient of variation was determined by expressing the standard deviation as a percent of the mean. A single moisture determination took about four minutes. A problem with these meters is they can't predict moisture in real-time. A real-time moisture sensor is capable of predicting moisture at the speed which material flows through the machine.

A different study utilizing soybeans found that an impact noise is generated when sending a sound wave through two materials (Luz and To, 2001). The two materials used were grains and a metallic chamber. The impact noise was related to the physical properties of the materials. A Fast Fourier Transform (FFT) was performed on an acoustical frequency spectrum from soybeans and then slices of the frequency spectrum were made. The area under the curve in these slices is compared to the moisture content levels. This area generally decreased as the moisture content increased. The 3 kHz frequency band slice proved to be the best area for predicting moisture content of larger grain varieties. An $R^2 = 0.95$ with a coefficient of variation equal to 8.73 % MC wet basis was found for soybeans (Luz and To, 2001).

Near infrared reflectance (NIR) can be used to predict moisture as well as other material characteristics. Currently NIR can estimate the moisture content of ground cereal grains, tobacco, peat, and foodstuffs to better than 0.5% moisture content (Hooper, 1980). This accuracy is achieved through good sample preparation or scanning a large amount of the sample for multiple readings. NIR devices are commercially available in various bandwidth ranges. The NIR technique for moisture measurement is typically based on comparing the reflectance of wavelengths affected and not affected by water content. In the 1100 to 2100 nm wavelength range strong water absorption relationships were found at 1440 nm and 1930 nm (Hooper, 1980).

A solid state device emitting radiation at 1.30 μm and 1.45 μm was used to estimate the moisture content of Sabrina ryegrass (Bowman et al., 1985). These wavelengths were chosen based on a prior study and resulted with the 95% confidence limit being plus or minus 10.6 percent of a single measurement. The absorption at wavelength 1.30 μm was insensitive to water while absorption at the wavelength 1.45 μm wavelength was sensitive to water (Bowman et al., 1985). For Talbot variety grass in the moisture range of 40-80 %MC wet basis a single point measurement was plus or minus 6.5 %MC wet basis using NIR (Stafford et al., 1989).

Dynamic NIR moisture measurements in self-propelled forage harvesters have yielded standard deviations of less than 3 %MC wet basis and R^2 values of more than 0.90 (Kormann and Auernhammer, 2002). The NIR measuring location was in the self-propelled forage harvester's spout. Material passed by the sensor quickly so measurements could only take a fraction of a second. A different study scanned the material for six seconds to acquire the desired 4096 microprocessor cycles (Bowman et al., 1985). This method yielded a correlation coefficient of 0.9893 and a 95% confidence limit of plus or minus 10.6 %MC wet basis.

Since NIR is based on reflectance measurements the moisture content predictions are based on the materials surface presented to the NIR equipment which may not necessarily be the moisture content of the material. It was found that the reflectance property of leaves is a good indicator of the presence of spray droplets on the leaf surface (Ramalingam et al., 2001). This study found a correlation coefficient of 0.8942 for a linear regression between the amount of water added on top of each leaf and the radiative equivalent water thickness difference, which is not the overall moisture content of the material being analyzed.

If the material being measured is not homogeneous then both NIR and impedance measurements may have inaccurate readings. An example is that the diameter of alfalfa stems affects measured NIR and impedance values. Even though stem diameters have a small range, a minor change in them results in a large change of electrical impedance (Walton, 1973). NIR measurements can show inaccuracies of drying stems by underestimating the moisture content of them (Hooper, 1980). The inaccuracies develop from the varying stem drying times. A thick stem will take longer to dry than a thin stem. Since the stem's inside is the last to dry down the center may remain moist while the outside is dry. Another consideration is that it takes stems much longer to dry than the leaves (Hooper, 1980). NIR measuring systems are problematic since they only see the surface. Impedance measurements can be problematic if a wide range of stem diameters exist. Impedance measurements can be calibrated at one stem size but measurements may have errors for other stem sizes without calibrations (Walton, 1973).

Other methods of rapid moisture content prediction have been performed on many agricultural materials utilizing their dielectric properties (Nelson, 1999). Predicting moisture content of cereal grains from their dielectric properties has been researched for over 90 years and used for over 50 years (Nelson, 1999). The complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ is composed of real and imaginary components. The real component is the dielectric constant, ε' and the imaginary component is the dielectric loss factor, ε'' . Both are of interest for dielectric measuring techniques. The dielectric constant is associated with the energy storage of the electric field in the material and the loss factor is associated with energy dissipation in the material or the conversion from electric energy to heat energy (Nelson, 2003). Temperature affects both the dielectric constant and loss factor. It has been shown for some fruits and vegetables that the dielectric loss factor generally increases with increasing temperature (Nelson, 2003). It has also been shown that for increasing temperatures the dielectric constant increases at lower frequencies but decreases at higher frequencies for some fruits and vegetables. A point between 10 MHz and 100 MHz is the transition point where no effect was observed for increasing temperatures.

Another study shows without temperature correction the predicted moisture would increase linearly with temperature at 20 MHz (Mesazaros and Funk, 2003). Current commercial grain meters sensing permittivity predominately operate in the frequency range from 1 MHz to 20 MHz (Nelson and Trabelsi, 2002). Grain meter limits for low temperatures are determined to be 12% for sunflowers, 20% for soft wheat, 19% for autumn barley, 19% for oats, 11% for rapeseed, and 19% for soybeans (Mesazaros and Funk, 2003). If real grain moisture content were above these limits than any additional water in the grain beyond the limit would not be sensed with radio frequency measurements at below freezing grain temperatures.

Density effects were noticed while measuring the dielectrics of a yellow dent field corn. Under increasing pressure the dielectric constant and dielectric loss increase more dominantly at low frequencies than at high frequencies (Gillay and Funk, 2003). Resistance-based impedance measuring systems are also affected by the pressure between the material

and the sensor plates. If the pressure applied between cotton and electrodes is higher than during calibration increased moisture content is indicated (Byler et al., 2003).

In a forage moisture content measurement study, an increase in pressure resulted in a corresponding decrease in resistance (Joannis et al., 2004). It was also noticed that at high pressure levels the affect of pressure changes on moisture prediction was less critical. A possible explanation for this relationship is that there were limits on the conductivity of the material.

Some studies have accounted for the bulk density affects by multiplying the moisture content by the bulk density. The product is sometimes referred to as the moisture density, which is found to be an important prediction variable for moisture measurements using radio frequency impedance techniques (Kim et al., 2003). Another study has shown that bale densities after compression, also referred to as relaxed densities, increase with temperature (Keleny et al., 1988). Bulk density effects and temperature are only two of the factors to consider when designing a sample test cell.

To minimize external influences on measurement test cells, they must be shielded (Gillay and Funk, 2003b). A shield will change the test cell characteristics significantly and these changes are accounted for during its design. The shield effects depend largely on the parallel plate separation distance and the ratio of the sensing area to shielding area. Cable types and connectors have parasitics, which may also affect sensing accuracy.

Through dielectric measurements the permittivity can be acquired by measuring attenuation and phase shift. It has been shown that both change in a relatively linear fashion with changes in grain moisture content (Kraszewski, 1988). Attenuation describes the power loss an electromagnetic wave undergoes when propagating through a medium (Trabelsi and Nelson, 2003). This can be found by the power level difference with and without the sample between the parallel plates. The phase shift reflects the delay in propagation caused by the slowing speed of the wave propagation in the medium. The ratio of phase shift over

attenuation has been considered for density independent determinations of grain moisture content. Another density independent method for finding the moisture content is using the complex plane plot of ϵ'/ρ vs. ϵ''/ρ where different moisture contents are aligned along the same straight line (Trabelsi et al., 1998). This complex plane plot is also known as the Cole-Cole plot or an Argand diagram. An increase in moisture content or temperature will shift recorded measurements up the line. From these variables moisture estimation is made possible for many uniform agricultural materials.

Moisture prediction of individual peanut pods and kernels is possible by measuring the complex impedance of a parallel plate capacitor. The differences in capacitance, dissipation factor and phase angle are used at frequencies of 1 MHz and 5 MHz. Predicted moisture contents of individual kernels using these three factors were within 1% accurate for over 90% of the kernels tested (Kandala, 2003). When estimating small samples of 6 to 8 kernels the moisture was predicted within 1% of air oven values for over 85% of samples tested (Kandala and Nelson, 2003).

Powers of 50 or 250 watts were applied to wilted grass after going through a forage harvester to predict moisture content. The frequency generator was set at 27.12 MHz and the impedance was set to 50 ohms. These settings yielded an adjusted $R^2 = 0.94$ when estimating water mass (Snell et al., 2001). Increasing the power didn't improve accuracy but increasing the sample density of wilted grass did improve the prediction accuracy. A high correlation was also achieved for predicting the water mass of chopped maize (Oberndorfer et al., 2001). Another study using this same measuring technique could accurately predict the mass of summer wheat with an $R^2 = 0.9996$ (Snell and Lucke, 2003). The time at which summer wheat readings were taken was based on the presence of reflected power. A mass measurement was taken after reflections were no longer present, which took from five to fifteen seconds.

Moisture prediction of hay and forage has been attempted using a parallel-plate capacitor setup where the frequency changed according to moisture content. A reference frequency of

854 kHz was set on an LM 555 integrated circuit timer. Its frequency dropped as the amount of water increased in the sensing volume (Osman et al., 2002). The increase in water was from either a material's increased moisture content or an increased amount of material in the sensing volume. Both conditions will result with more water being in the sensing volume. Frequency drop was better correlated to water mass at lower water densities than at higher water densities (Osman et al., 2002). The frequency drop was only significant between 27-44% moisture content of alfalfa at low density. After converting the alfalfa moisture content into water mass the $R^2 = 0.67$ (Osman et al., 2003). This method could not directly estimate the moisture content of material in the sensor volume. Moisture content can be determined with this method if the total wet mass and mass of water was already known. Another dielectric measurement system also concluded the estimate of water mass is more precise than of the dry matter content (Oberndorfer et al., 2001).

Dynamic tests with a capacitance controlled oscillator show that frequency drop increased linearly with mass and the slope was related to moisture content (Martel and Savoie, 2000). With alfalfa the R^2 ranged from 0.53 to 0.59 percent and the RMSE ranged between 9.3 and 9.9 %MC wet basis. Timothy showed an R^2 of 0.74 to 0.78 with the RMSE between 9.4 and 10.9 %MC wet basis. The test setup consisted of feeding pre-chopped forage on a conveyor belt into a Dion model 1660 flywheel type blower which had a spout fitted onto it. The parallel plates for the oscillator were mounted at the end of the spout which the forage passed through. The oscillator used was a TS555CN timer with the reference frequency set to 880 kHz. Another dynamic test was performed mostly on wilted timothy grass from 45 to 78 percent moisture content in the field with the same oscillator. Here the oscillator correlated to moisture content better with $R^2 = 0.662$ than to wet mass-flow rate of $R^2 = 0.468$ (Savoie et al., 2002). Mass flow prediction based on oscillator frequency drop was better in the lab than in the field (Savoie et al., 2002).

A study using multiple frequencies utilized three frequencies statistically picked from 250 sampled frequencies in the range of 1 MHz to 500 MHz. The frequencies of 1 MHz, 41 MHz, and 141 MHz yielded an $R^2 = 0.986$ for corn moisture with a standard error of 0.64

%MC wet basis (Lawrence et al., 2001). This study compared a fabricated parallel plate sample holder to the GAC 2100 moisture tester. Similar or better predictions were made with the parallel plate sample holder for hard red winter wheat, hard red spring wheat, soft red winter wheat, soft white wheat, hard white wheat, durum wheat, soybeans, long and medium grain rice, and yellow dent field corn.

Moisture content prediction for Korean short and medium grain rough rice, brown rice, barley and wheat can be done with multiple frequencies of 1 MHz, 5 MHz, and 10 MHz. The moisture content of rough rice predicted from the oscillator frequency, grain moisture density, and grain temperature yields an $R^2 = 0.985$ and $RMSE = 0.40$ percent moisture content (Kim et al., 2003). In this system moisture density increased as the dielectric properties increased and the oscillator frequency dropped.

A previous study at Iowa State University has shown that the determination of hay and forage moisture content prior to compaction was possible using impedance measurements of capacitive type sensors at multiple frequencies (Eubanks and Birrell, 2001). Impedance measurements of each sample were taken at sequential individual frequencies from 5 Hz to 13 MHz. A multiple linear regression to predict moisture content was used to obtain an equation utilizing multiple frequencies. The R^2 generally increased as the number of frequencies used for prediction increased. For density independent alfalfa moisture predictions $R^2 = 0.2249$ using the best single frequency. Using additional frequencies R^2 increases as follows: $R^2 = 0.7163$ for 2 frequencies, $R^2 = 0.7758$ for 3 frequencies, $R^2 = 0.8538$ for 4 frequencies, and $R^2 = 0.9532$ for 5 frequencies (Eubanks and Birrell, 2001). The increasing R^2 values for increasing factors also held true for brome grass, clover, orchard grass, a brome grass alfalfa mixture, and a brome grass clover mixture. The condition with 5 frequencies for density independent alfalfa moisture prediction yielded an $RMSE = 4.99$ %MC wet basis. The volume of material ranged from 25% to 100% of the sensing volume. The high density filled 100 percent of the volume and had a mass eight times greater than the 25 percent volume filled low density. This study also found the developed prediction equations were dependent on the material type.

Objectives

In the previous study performed at Iowa State University predicting hay and forage moisture content took many seconds to record a measurement while frequencies were sequentially scanned. The objective is to develop and test a system capable of real-time hay and forage moisture sensing. To achieve this sensor hardware and signal conditioning circuits are required to take multiple frequency measurements at the same time. Since sequentially scanning frequencies is not fast enough frequency measurements need to be taken simultaneously. The development of a multi-frequency dielectric simultaneous sampling technique and its performance evaluation will be covered in the following papers.

CHAPTER 2. DEVELOPMENT OF A MULTI-FREQUENCY DIELECTRIC SENSING SYSTEM FOR REAL-TIME FORAGE MOISTURE MEASUREMENT

Paper Number: 041100

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Abstract

A previous study at Iowa State University has shown promise for the determination of hay and forage moisture content prior to compaction using multi-frequency dielectric measurements. This previous study used a sensing system that took sequential frequency measurements which takes considerable time. Due to the fast material flow through equipment, the measurements need to be taken in a very short time period. Taking multi-frequency dielectric measurements “simultaneously” will ensure all frequencies measurements are from the same sample mass.

This paper will report on the development of the sensing hardware for “simultaneous” multi-frequency dielectric measurements and the evaluation of the system under static test conditions. Ideally, the measurement system will be capable of predicting the moisture content independent of density, material volume, and material composition.

Introduction

Moisture content usually shows the hay quality which affects harvesting, storing, buying, and selling of hay and forage (Eubanks and Birrell, 2001). Hay and forage is marketed on a wet weight basis so profits are optimized when harvesting in the optimal moisture range. More leaves fall off during the harvest of low moisture content hay making it a lower quality and producers will have a lighter product yielding lower profits. At the other extreme storing hay too wet can cause spoilage and possibly internal combustion.

A preservative needs to be added during harvest to successfully harvest and store wet hay. Unfortunately, hay preservatives are relatively expensive so they are not economical for everyday use. However, preservatives may become a more profitable option when avoiding

rain on the crop. If the crop mass flow rate and the moisture content are known, then preservative application can be applied in a variable rate fashion thus saving the producer money. The most common hay preservative to reduce storage losses is propionic acid which is supposed to reduce microbial growth and subsequent heating (Shinners, 2000).

Various methods to determine moisture content that are developed or being developed includes oven drying, electric meters, NIR spectroscopy, and dielectric measurements. The baseline for hay moisture measurement comparisons is oven drying using ASAE Standard S358.2 (ASAE, 2003). This standard requires a representative sample to be in the oven for 24 hours at 103 degrees Celsius or for 72 hours at 60 degrees Celsius. Electronic meters are currently the most widely used method commercially to determine hay and forage moisture content (Henson et al., 1987). NIR spectroscopy using microwave reflections and capacitive systems can also predict forage moisture content (Kormann and Auernhammer, 2002). Dielectric moisture measurement sensors have shown potential in the radio frequency range (Eubanks and Birrell, 2001). Many of the current moisture sensors available determine the moisture content after bale formation. These capacitive sensors operate at a single frequency making them sensitive to hay density. Therefore, field calibrations are required to account for varying bale density and ambient conditions.

For a number of years grain moisture sensors using capacitive type methods and other impedance measurements have been in widespread commercial use. The dielectric properties of several grains are specified in ASAE Standard D293.2 (ASAE, 1998). Measured impedance depends on both the moisture content and the bulk density of the sample. Many of these moisture sensors require also field calibrations to account for the changes in sample density. The development of density-independent functions of the dielectric properties of grains has been and still is being investigated in both the radio and microwave frequency ranges (Gillay and Funk, 2003a; Nelson and Trabelsi, 2002). It was also found that dielectric constants vary according to temperature and frequency for grains (Nelson, 2003).

A previous study at Iowa State University has shown the determination of hay and forage moisture content prior to compaction was possible using impedance measurements of capacitive type sensors at multiple frequencies (Eubanks and Birrell, 2001). Impedance measurements of each sample were taken at sequential frequencies from 5 Hz to 13 MHz at a rate of one frequency every three seconds. A multiple linear regression to predict moisture content was used to obtain an equation utilizing multiple frequencies. Multiple linear regressions were used because the R^2 values generally increased the moisture prediction accuracy using many frequencies. For density independent alfalfa moisture predictions $R^2 = 0.2249$ using the best single frequency. Using additional frequencies R^2 increases as follows: $R^2 = 0.7163$ for 2 frequencies, $R^2 = 0.7758$ for 3 frequencies, $R^2 = 0.8538$ for 4 frequencies, and $R^2 = 0.9532$ for 5 frequencies (Eubanks and Birrell, 2001).

It takes many seconds to record a multi-frequency measurement using the sequential frequency method. A real-time moisture sensor must be capable of predicting moisture at the speed which material flows through the machine. A real-time sensor does not have many seconds to take a measurement. Large amounts of material will have passed through the sensing volume in a few seconds. The first frequency would measure one sample mass and the final frequency would measure an entirely different sample mass. Taking multi-frequency dielectric measurements simultaneously would ensure all measurements are from the same sample mass. This would minimize the effects of material flow on moisture prediction.

Objectives

The objective is to develop a system capable of real-time hay and forage moisture sensing. A previous study taking sequential frequency measurements took many seconds which is impractical for a real-time moisture sensor. A real-time moisture sensor should have multiple frequency measurements taken simultaneously to ensure all measurements are from the same sample mass. Specific objectives include:

- 1) Develop sensor hardware and signal conditioning circuits required for simultaneous multi-frequency dielectric impedance measurements.

- 2) Determine if sequential frequency measurements are comparable to measurements taken from extracted frequencies of a multiple frequency signal.

Theory

Impedance measurements taken in a known sensing volume on a particular material determines the material's dielectric properties. The complex permittivity, ϵ , is defined as,

$$\epsilon = \epsilon' + j\epsilon'' \dots\dots\dots(1)$$

where ϵ' is the real part known as the dielectric constant and ϵ'' is the imaginary part known as the dielectric loss factor. The dielectric constant is associated with the energy storage of the electric field in the material and the dielectric loss factor is associated with energy dissipation in the material or the conversion from electric energy to heat energy (Nelson 2003). The loss tangent is,

$$\tan(\delta) = \frac{\epsilon''}{\epsilon'} \dots\dots\dots(2)$$

where δ is known as the loss angle. The capacitance of a parallel plate sensor is determined from the dielectric constant, area of the sensor plates, A, and the distance between the sensor plates, d, as follows,

$$C = \frac{\epsilon' A}{d} \dots\dots\dots(3)$$

The dielectric constant is composed of a relative material dielectric constant, ϵ'_r , and the permittivity of free space, ϵ_0 , as shown,

$$\varepsilon' = \varepsilon_0 \varepsilon'_r \dots\dots\dots(4)$$

where ε_0 is equal to 8.854×10^{-12} F/m. The free space capacitance, C_0 , for a particular parallel capacitor is determined as,

$$C_0 = \frac{\varepsilon_0 \varepsilon'_{air} A}{d} \dots\dots\dots (5)$$

where the relative dielectric constant of air, ε'_{air} , is equal to one. A material's capacitance, C_{mat} , is used when the sensing cell is filled with that material as shown,

$$C_{mat} = \frac{\varepsilon_0 \varepsilon'_{mat} A}{d} \dots\dots\dots (6)$$

where, ε'_{mat} , is the relative dielectric constant of the material. The real part of the complex admittance is the conductance, G , and is determined as,

$$G = 2\pi f C_0 \varepsilon'' \dots\dots\dots (7)$$

where G is a function of frequency, f , empty cell capacitance, C_0 , and the dielectric loss factor, ε'' . The susceptance, B , is the imaginary part of the admittance and related to the capacitance as follows,

$$B = 2\pi f C_{mat} \dots\dots\dots (8)$$

When modeling the Device Under Test's (DUT) complex impedance as a parallel resistor and capacitor, the conductance, G , and susceptance, B , are related to DUT impedance, Z_{DUT} , as follows,

$$\frac{1}{Z_{DUT}} = G + jB \dots\dots\dots (9)$$

After substituting the conductance and susceptance into equation 9 the DUT impedance becomes,

$$Z_{DUT} = \frac{1}{2\pi f \epsilon'' \frac{\epsilon_0 \epsilon'_{air} A}{d} + j2\pi f \frac{\epsilon_0 \epsilon'_{mat} A}{d}} \dots\dots\dots (10)$$

Sensor Circuit Development

The overall sensor circuit is shown in Figure 1 and is designed to find the DUT impedance. The equivalent impedance, Z_{eq} , is a resistor, R_1 , in series with the DUT impedance and from this relationship Z_{eq} can be determined as,

$$Z_{eq} = Z_{DUT} + R_1 \dots\dots\dots (11)$$

The signal going to the DUT is driven by operational amplifier (OP-AMP) 1 and this driven signal, V_1 , is recorded by the data acquisition system via buffer amplifier OP-AMP 4 shown in Figure 1.

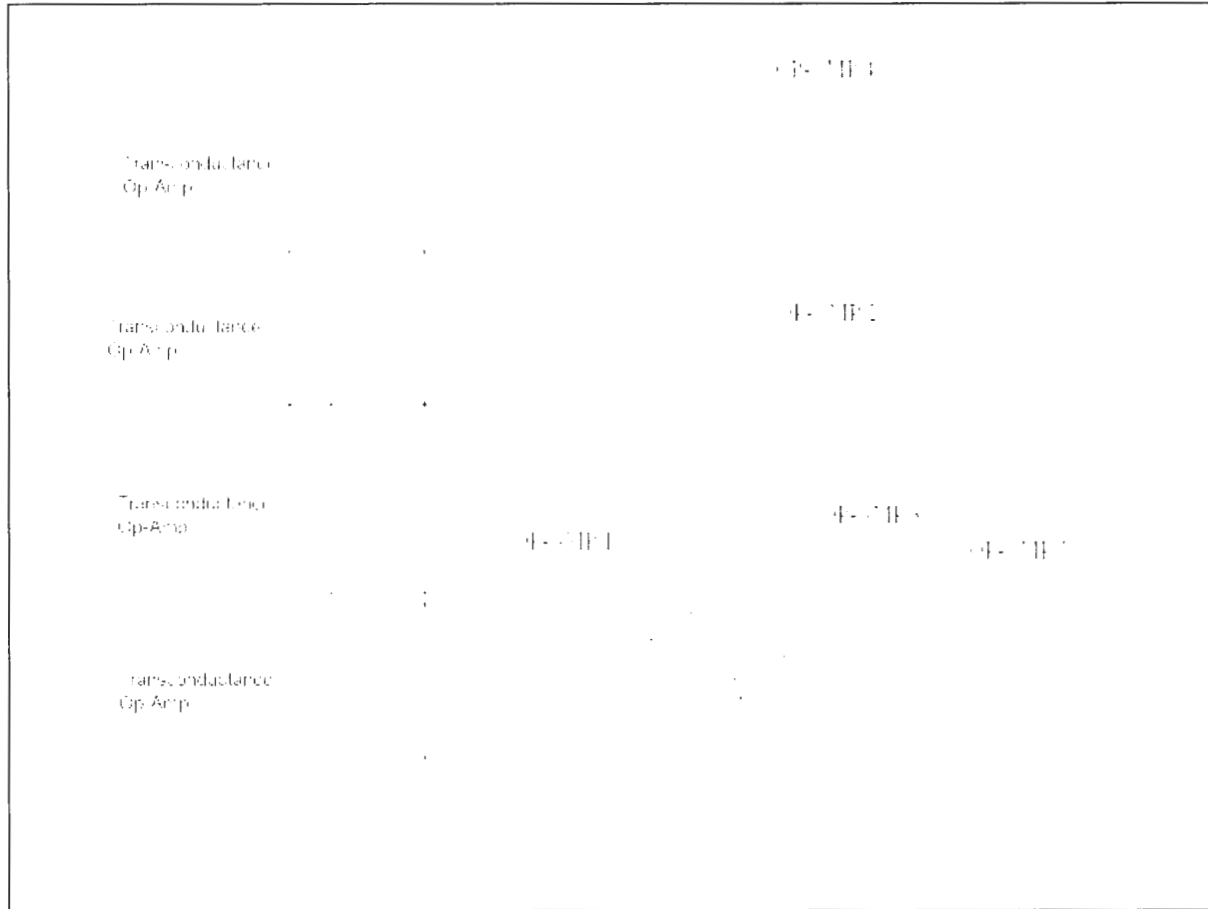


Figure 1. Schematic of auto-balancing bridge sensor circuit with buffer operational amplifier drivers for the sensing signal, guard signal, and buffered data acquisition signals.

The auto-balancing bridge is the standard method of measuring impedance at frequencies less than 40 MHz and shown as OP-AMP 3 which is the operational amplifier after Z_{eq} (Agilent Technologies, 2003). The auto-balancing bridge is based on the flow of current. For all operational amplifiers both the inverting and non-inverting inputs are always at the same voltage, unless saturated. The non-inverting input of OP-AMP 3 is connected to ground through a resistor which makes the inverting input a virtual ground. With the inverting input a ground the voltage drop across Z_{eq} is related to the current flowing through it as follows,

$$I = \frac{V_1}{Z_{eq}} \dots\dots\dots (12)$$

An equal amount of current also flows through a feedback resistor, R_3 , because amplifier input current is negligible. This current is related to R_3 and the voltage after the auto-balancing bridge, V_3 , as follows,

$$I = \frac{-V_3}{R_3} \dots\dots\dots(13)$$

The current in equation 12 is equal to the current in equation 13 allowing,

$$\frac{V_3}{V_1} = -\frac{R_3}{Z_{eq}} \dots\dots\dots (14)$$

The attenuation is measured by dividing the signal output from the auto-balancing bridge by the driven signal to the first sensor plate. The phase shift can be found by subtracting the input phase from the output phase. Both the attenuation and phase relationship are shown as,

$$\frac{V_3}{V_1} = \left| \frac{V_3}{V_1} \right| \angle(\phi) \dots\dots\dots (15)$$

where phase shift, ϕ , is equal to the phase of the driven signal, ϕ_3 , minus the phase of the signal output from the auto-balancing bridge, ϕ_1 . Signals measured with the data acquisition system correspond to the attenuation and phase shift as follows,

$$\frac{V_A K}{V_B} = \frac{V_3}{V_1} \dots\dots\dots (16)$$

where V_A is the signal coming from OP-AMP 5 going to channel A of the data acquisition, V_B is the signal coming from OP-AMP 4 going to channel B of the data acquisition, and K is a constant which equals 0.3282 and accounts for the amplifier gains of both data acquisition

measured signals. The signals measured with the data acquisition are related to the equivalent impedance as,

$$Z_{eq} = -\frac{R_3 \mathbf{V}_B}{K \mathbf{V}_A} \dots\dots\dots(17)$$

From equations 11 and 17 the material dielectric constant and dielectric loss factor can be determined.

Apparatus

The method used in this study to measure impedance is based a parallel plate setup. A pre-determined signal goes to the first sensor plate while the second sensor plate connects to the auto-balancing bridge. From research performed by another researcher in this area it was determined that the sensing area should be shielded to protect it from outside influences (Gillay and Funk, 2003b). It was decided for this study to have the sensor plate insulated from the hay bale using acrylic material. The sensor plate is also shielded with a guard area around the outside edge and back side of it. The guard signal for both plates is connected to the guard plate through the screws of the SMA flange connector as shown in Figure 2. The guard plate of the first sensor plate assembly was driven by a buffered voltage signal, V_2 , equal in magnitude and phase, as the sensor signal, V_1 , driving the sensor plate. The second sensor plate assembly guard is connected to ground at the circuit boards. The sensing section area is 297.3 cm^2 and the guard section area is 305.0 cm^2 . Stands were made to hold the sensor plate assemblies vertical and parallel to each other. The sensor plates are placed 49.6 cm apart with a hay bale between them oriented with its strings down. The hay bale analyzed was 54.7 percent moisture content wet basis.

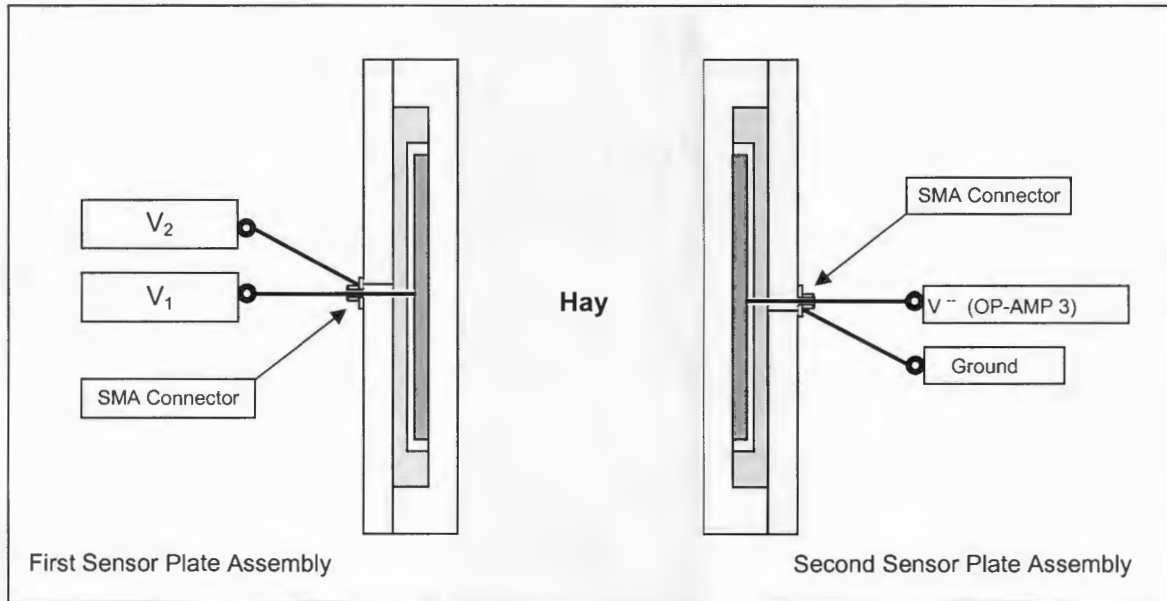


Figure 2. Cross sectional view of the sensor plate configuration showing the sensor plates (in red), acrylic insulators (in blue) and guard plates (in orange).

Two different circuit boards were developed to make the multi-frequency impedance measurements. The first circuit board developed is a frequency generating board which outputs a sine wave at a particular set frequency. The second board developed is an analog signal board used to combine the individual frequencies signals and contains the buffered drivers and auto-balancing bridge circuit. Circuit boards are designed to be stackable and connect together through a header. The stackable circuit boards are shown in Figure 3 with one analog signal board connected to two frequency boards. The analog board can sum together a maximum of four frequencies coming through the header. If less than four frequencies are desired fewer frequency boards are needed.

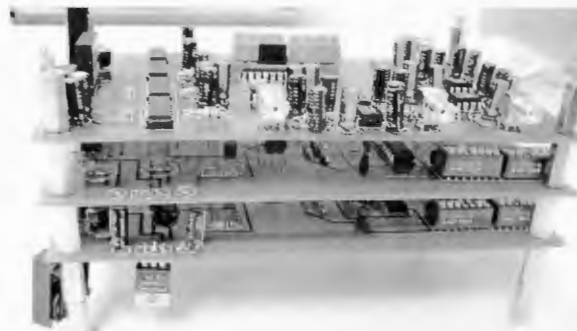


Figure 3. Stackable circuit boards.

Based on a previous study performed at Iowa State University four frequencies were chosen and are 1 MHz, 3 MHz, 7 MHz, and 13 MHz (Eubanks and Birrell, 2001). The analog circuit is capable of selecting any combination of these four frequencies, providing up to fifteen different frequency combinations. The actual frequencies used are 1.035 MHz, 2.863 MHz, 7.132 MHz, and 13.431 MHz but are referred to as 1 MHz, 3 MHz, 7 MHz, and 13 MHz throughout this paper. Electrical testing circuits were developed using Multisim 2001 and circuit layouts were made using Ultiboard 2001 (Electronics Workbench). Circuit boards were composed of FR-4 material with two copper layers and were produced by a supplier.

Each frequency board contains a frequency generating chip, MAX038, to create the set frequency which is output to the header. Dip switches adjust the output voltage of a multiplying D/A converter, MX7541. This output voltage is converted to a current which adjusts the frequency output of the MAX038 frequency generating chip. The dip switches ensure a repeatable frequency selection thus minimizing frequency drift. Dip switches were also used in order to make all frequency boards the same while still being able to output various frequencies.

The analog signal board takes each individual frequency from the header into a trans-conductance amplifier, MAX436. Each MAX436 output is connected to an input on an analog switching chip, PS392. The PS392 allows for any frequency combination to be summed together and output on one line. The selected frequency combination is controlled by four digital bits on a PMD-1208LS USB data acquisition board connected to a computer. Possible frequency combinations are limited by the number of frequency boards connected to the analog board. The combined frequency output from the PS392 is connected to the input of an OPA388P buffer amplifier, shown as OP-AMP 1 in Figure 1. The output of OP-AMP 1 is connected to the sensing area of the first sensor plate. This signal is also duplicated separately through two more buffer amplifiers OP-AMP 2 and OP-AMP 4. The output of OP-AMP 2 connects to the guard area of the first sensor plate and the output of OP-AMP 4 is connected to A/D channel B on the data acquisition.

The sensing section of the second sensor plate assembly is connected to the auto-balancing bridge input on the analog signal conditioning board. The output of OP-AMP 5 is connected to A/D channel A on the data acquisition system. The guard area of the second sensor plate assembly is connected to ground on the analog signal board.

The data acquisition system consists of two boards connected together with a header. One board is a dual channel, 12-bit, 105 MSPS IF sampling A/D converter with analog input signal conditioning (Analog Devices 10200 Evaluation Board). The other board has 32768 sample readings of buffer memory for each channel and communicates to the computer via a parallel cable (Analog Devices High-Speed Analog-to-Digital Converter FIFO (A) Evaluation Kit). The data acquisition system simultaneously records both analog channels of data at 100 MHz until 32768 readings are stored in FIFO memory. After A/D conversions the data is transferred to the computer and written to a file for further analysis.

Type RS-316 cables with SMA connectors were used to connect the signal board to the sensor plates with a cable length of 1.2 m. Two RS-316 type cables 304 mm long connected the signal board to the data acquisition system. Another two RS-316 type cables 304 mm long connected the 100 MHz clock signal to the data acquisition board. The 100 MHz clock was required to sampling trigger the ADC 10200 A/D.

Analysis and Discussion

Many different signals can be created using the developed instrumentation. The system could be used to sequentially output and record the response for each individual frequency, in the same manner as a standard impedance analyzer. In addition, the system was capable of developing different frequency combinations, where individual frequencies are summed together creating a multiple frequency signal where all frequencies are simultaneously superimposed on each other. Bandpass filters were developed to extract the individual frequencies from the multiple frequency combined signal. Unfiltered sequential signals for 1 MHz, 3 MHz, 7 MHz, and 13 MHz are shown in Figures 4, 5, 6, and 7 respectively. Figure 8 shows an unfiltered multiple frequency signal containing all four frequencies tested.

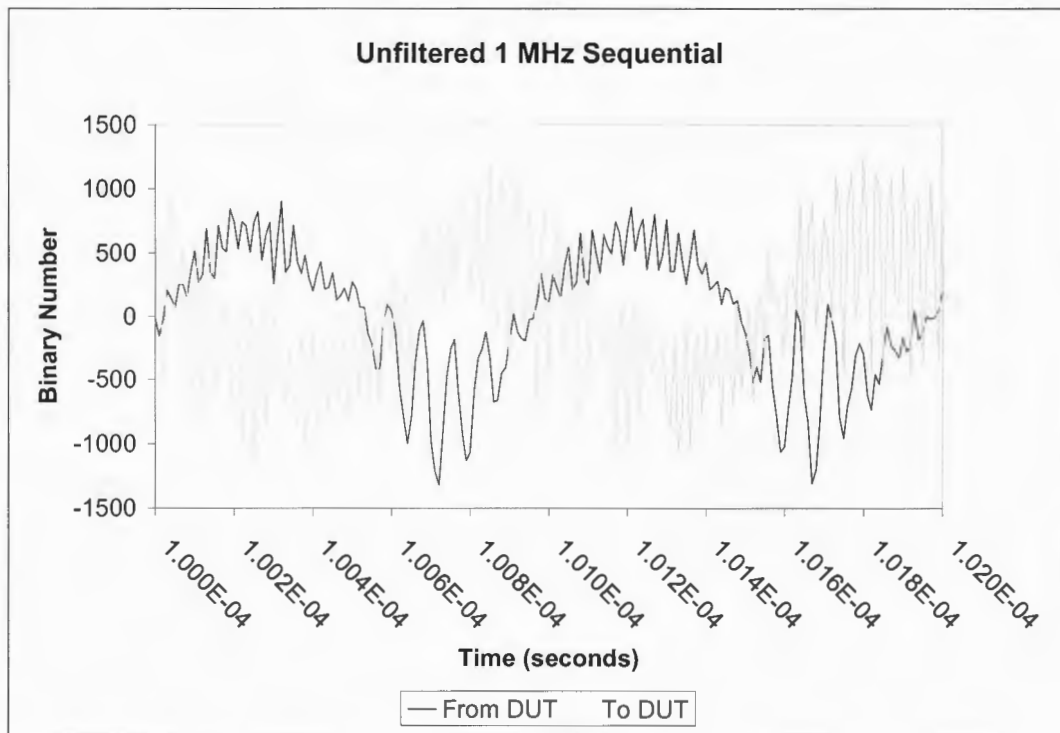


Figure 4. Unfiltered 1 MHz signal measured sequentially.

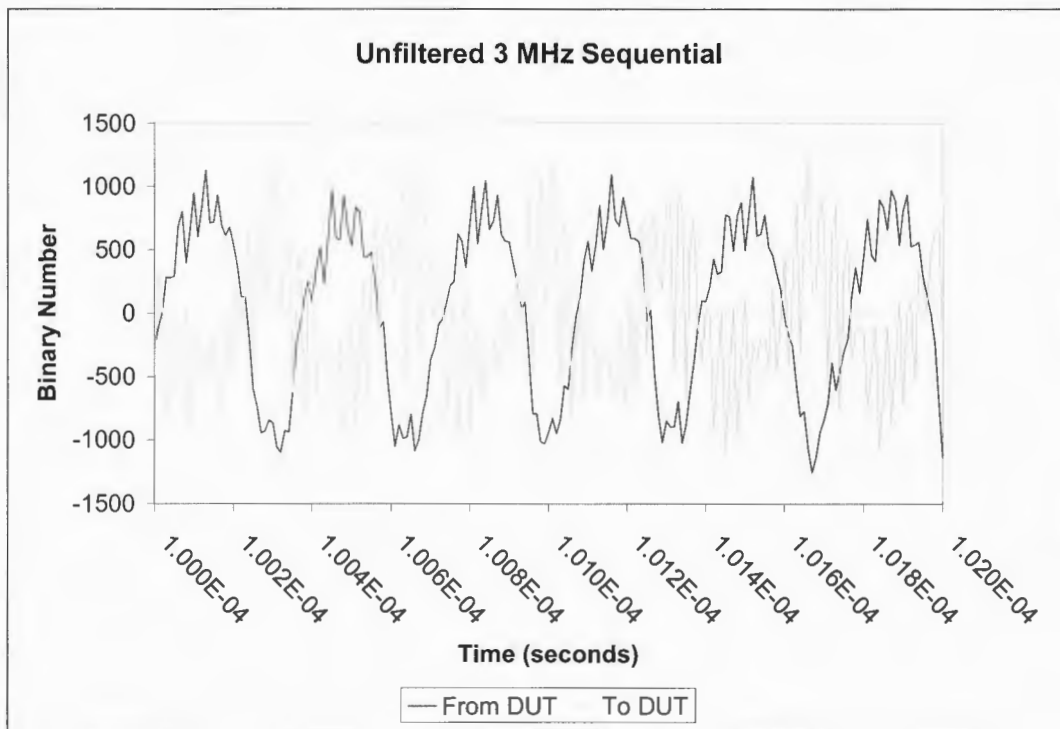


Figure 5. Unfiltered 3 MHz signal measured sequentially.

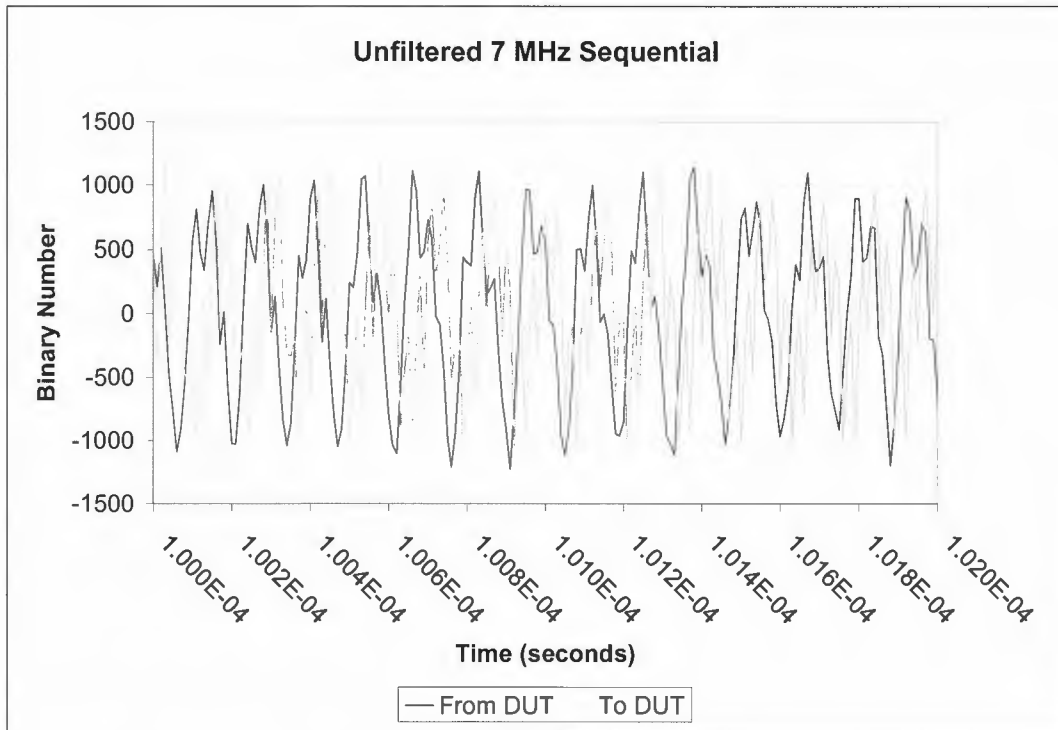


Figure 6. Unfiltered 7 MHz signal measured sequentially.

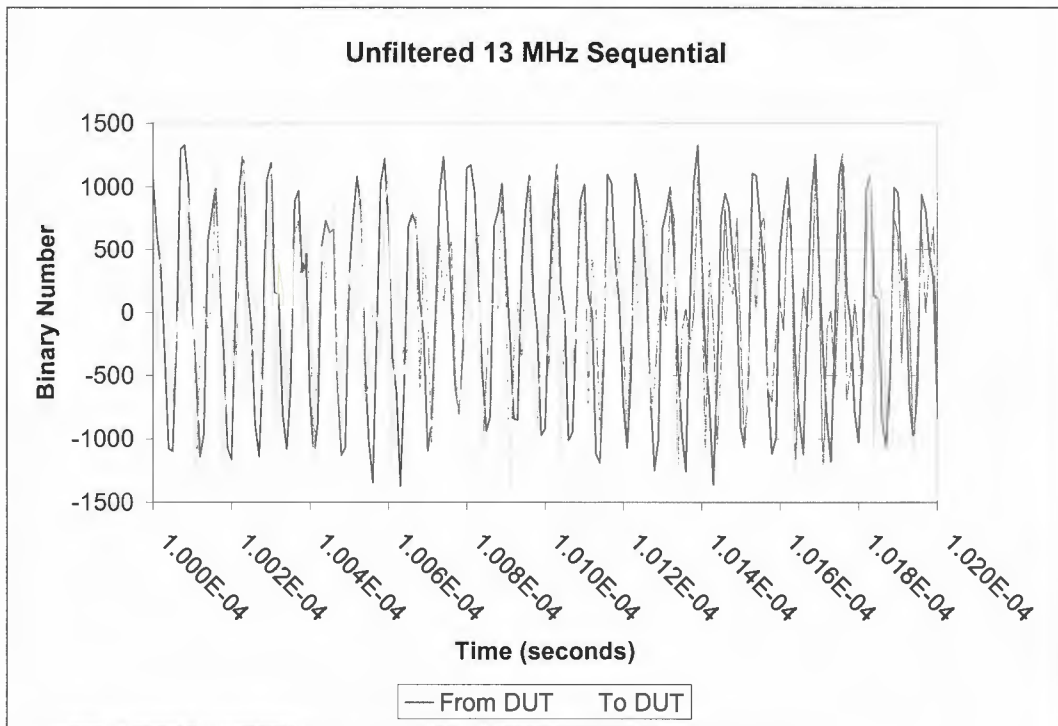


Figure 7. Unfiltered 13 MHz signal measured sequentially.

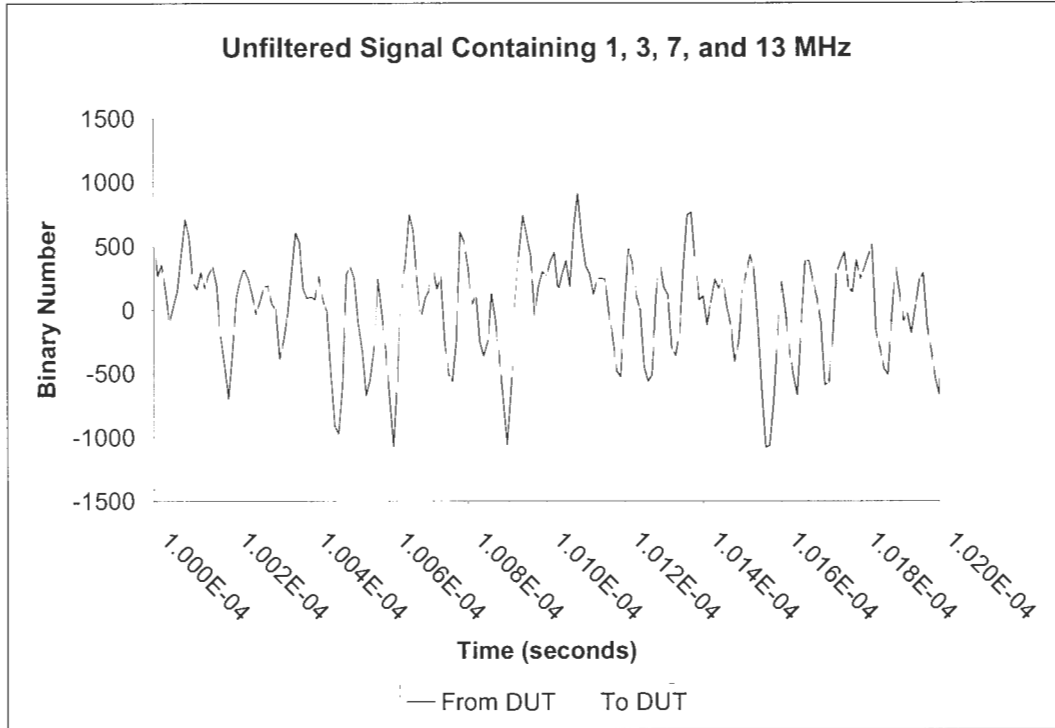


Figure 8. Unfiltered multi-frequency signal containing a sum of 1, 3, 7, and 13 MHz individual signals.

With the sample rate of 100 mega samples per second it takes 0.0003268 seconds to fill the buffer memory of the FIFO board of 32768 points. In this time period 339 cycles are collected for the 1 MHz signal, 938 cycles for the 3 MHz signal, 2337 cycles for the 7 MHz signal, and 4401 cycles for the 13 MHz signal. Since unfiltered signals going “To DUT” and “From DUT” all contained noise they were filtered using Matlab. Both individual frequencies and multiple frequency signals were filtered for desired frequencies using Bandpass FIR Equiripple filters with limits specified in Table 1.

Table 1. Matlab Bandpass FIR Equiripple filter parameters.

| Filter Parameters | Nominal Frequency | | | |
|---------------------------|-------------------|--------|--------|---------|
| | 1 MHz | 3 MHz | 7 MHz | 13 MHz |
| Passband Center Frequency | 1.035 | 2.863 | 7.132 | 13.431 |
| Low Stop Band Frequency | 0.91 | 2.738 | 7.013 | 12.211 |
| Low Pass Band Frequency | 0.9725 | 2.8001 | 7.0755 | 12.2735 |
| High Pass Band Frequency | 1.035 | 2.9255 | 7.2005 | 14.3985 |
| High Stop Band Frequency | 1.0975 | 2.988 | 7.263 | 14.461 |

After signal filtering the first 6000 collected points were not used because the signals were unstable in this region from the filtering process. Therefore, signal information is based from 277 cycles for 1 MHz, 766 cycles for 3 MHz, 1909 cycles for 7 MHz, and 3595 cycles for 13 MHz. Assume the average bale length is 91.44 cm (36 inches) and it takes 10 seconds to make one bale. This allows the entire sensing area to be in contact with the bale for 8.1 seconds. If only 0.0003268 seconds of data is collected and analyzed every second for 8.1 seconds then the average bale moisture is based on 2244 cycles for the 1 MHz signal, 6207 cycles for the 3 MHz signal, 15463 cycles for the 7 MHz signal, and 29121 cycles for the 13 MHz signal. In the time required to fill the buffer memory the hay bale will travel 0.03 mm showing this sensor is definitely fast enough to be considered a real-time sensor.

Filtered sequential frequencies of 1, 3, 7, and 13 MHz are shown in Figures 9, 10, 11, and 12 respectively. Sequential frequencies 1, 3, and 7 MHz show very clean signals after filtering. The filtered 13 MHz sequential frequency shows amplitude modulation on the signal.

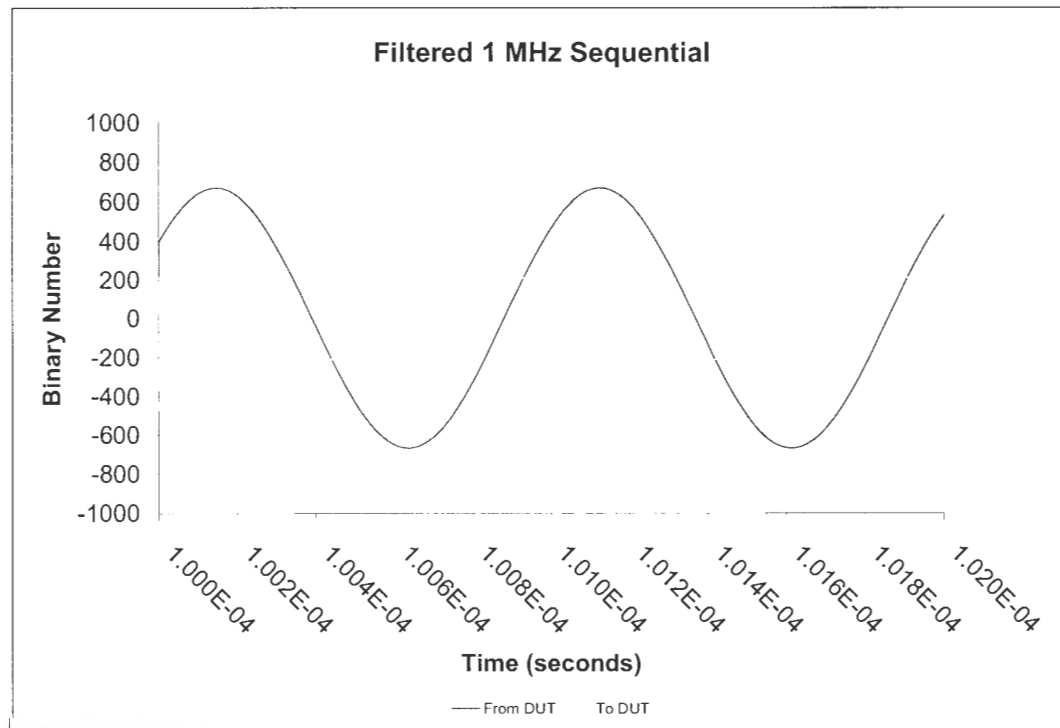


Figure 9. Filtered 1 MHz signal measured sequentially.

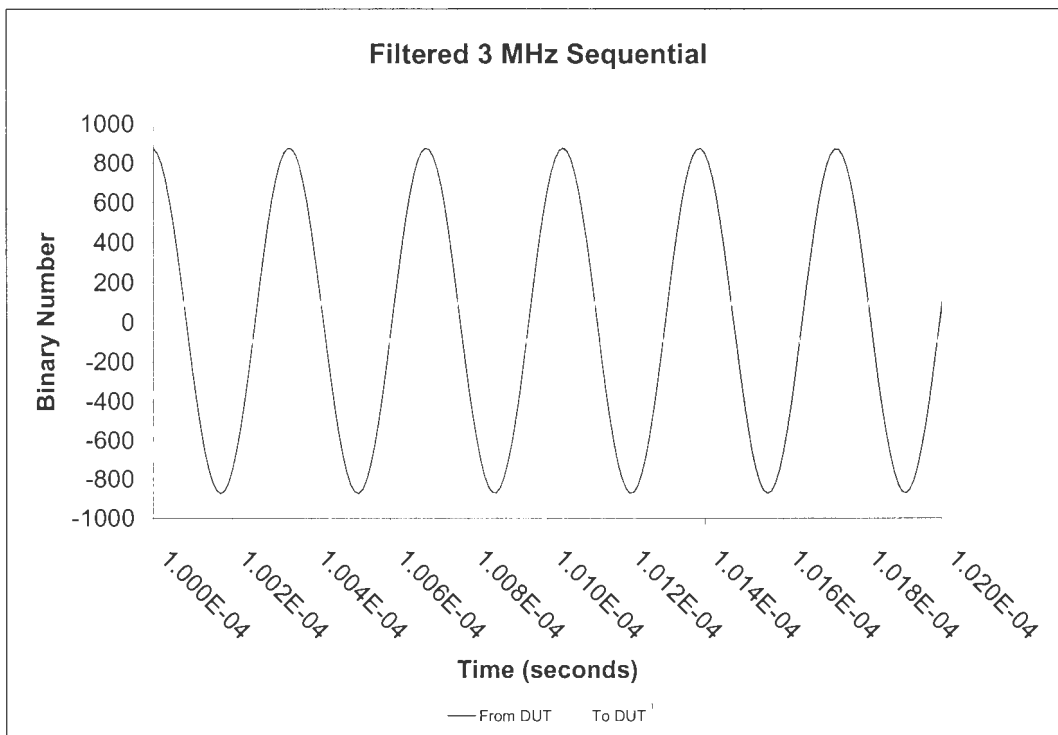


Figure 10. Filtered 3 MHz signal measured sequentially.

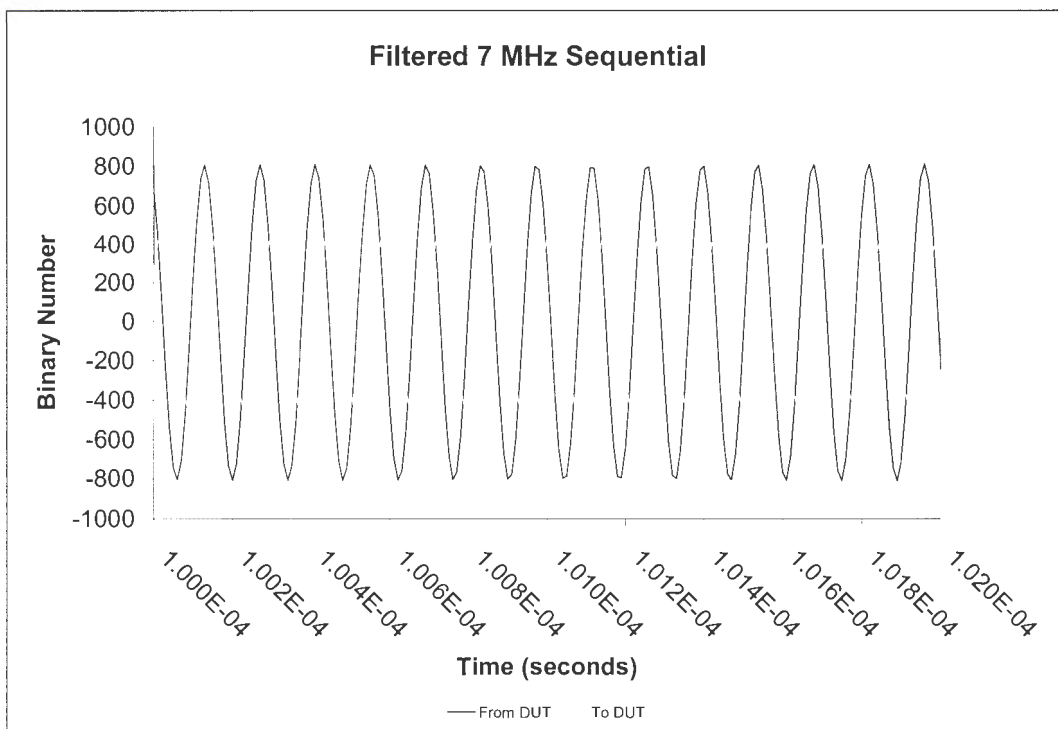


Figure 11. Filtered 7 MHz signal measured sequentially.

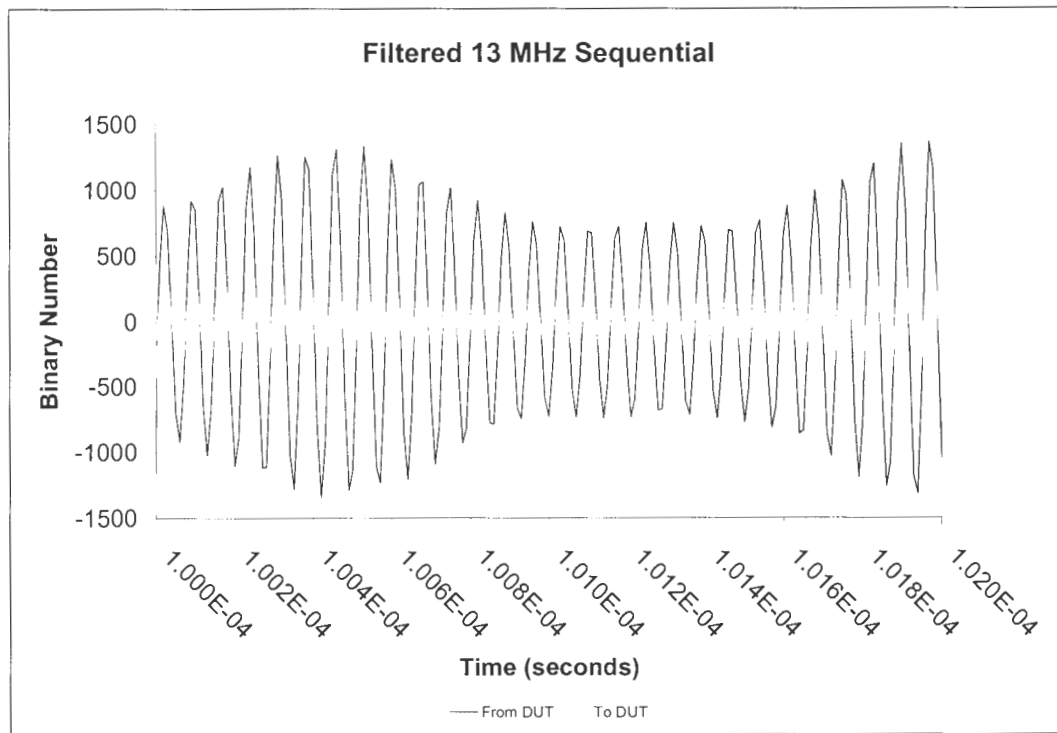


Figure 12. Filtered 13 MHz signal measured sequentially.

The multi-frequency signal containing the superimposed 1, 3, 7, and 13 MHz signals, was filtered to extract each frequency from the signal. Figure 13 shows a clean 1 MHz frequency extracted from the multi-frequency signal. Figure 14 shows a clean 3 MHz frequency extracted. Figure 15 shows a clean 7 MHz extracted. Figure 16 shows a 13 MHz extracted having amplitude modulation on the signal. This may have been caused by a number of factors including: sensor plate separation distance, improper cable terminations, improper circuit board terminations or trace widths. To achieve maximum resolution of the data acquisition the amplitudes of each frequency are reduced proportionally to the number of frequencies making up the multi-frequency signal. Since four frequencies make up the multi-frequency signal the amplitude of each extracted frequency is reduced to one-fourth of its sequentially scanned amplitude.

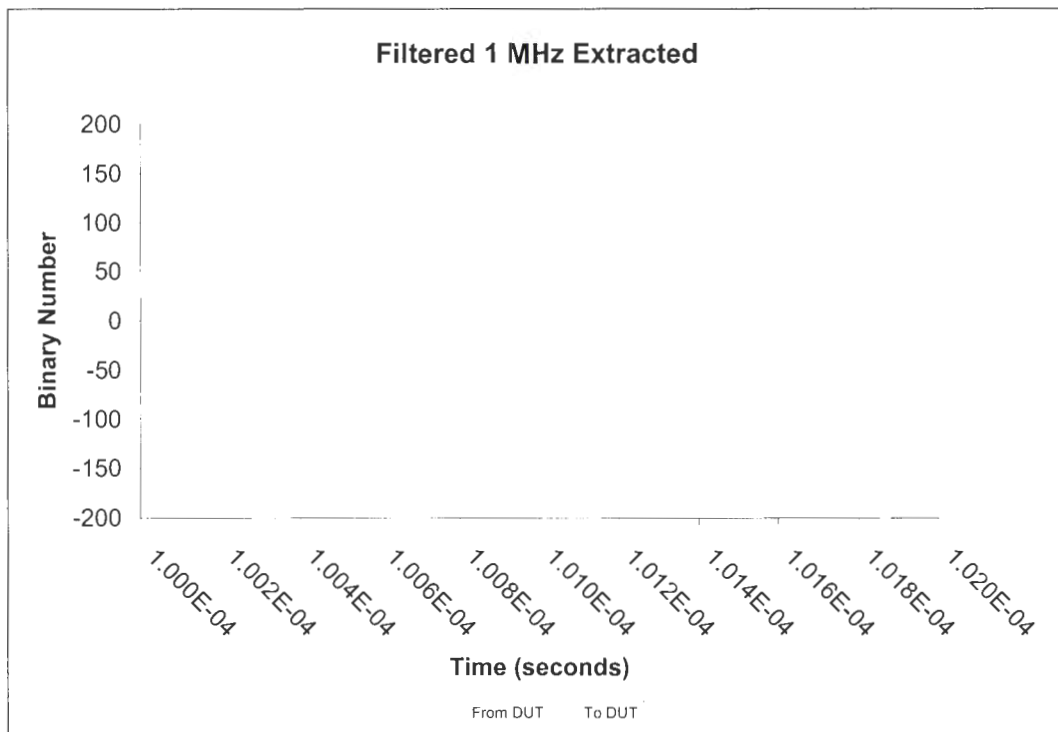


Figure 13. Filtered 1 MHz signal extracted from multi-frequency signal containing all four frequencies.

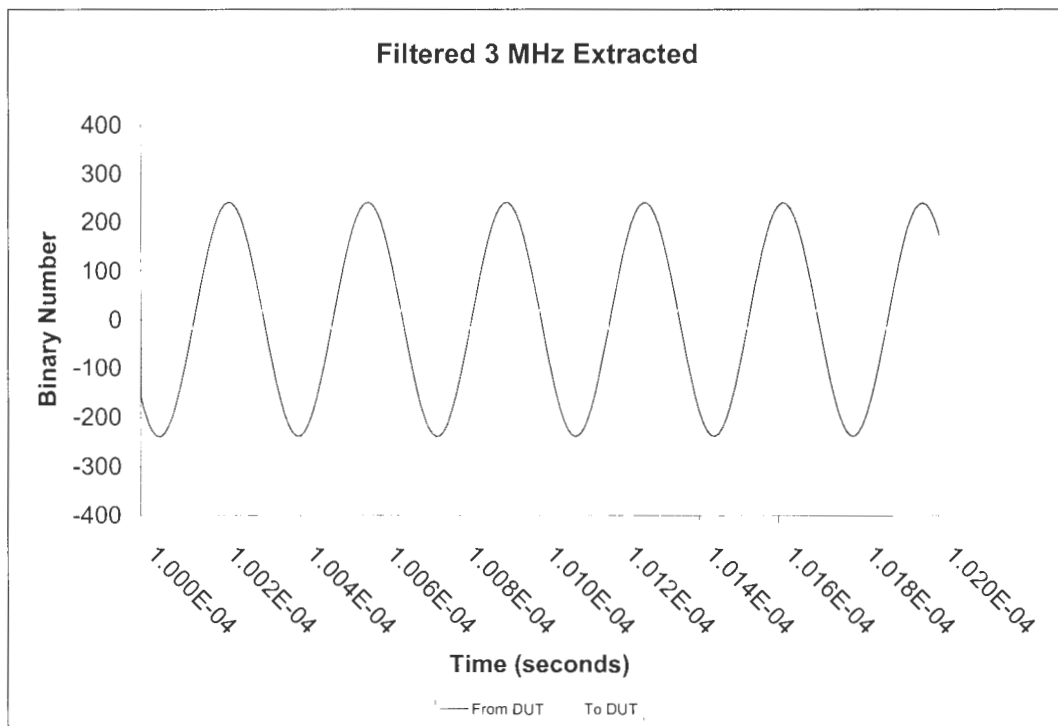


Figure 14. Filtered 3 MHz signal extracted from a multi-frequency signal containing all four frequencies.

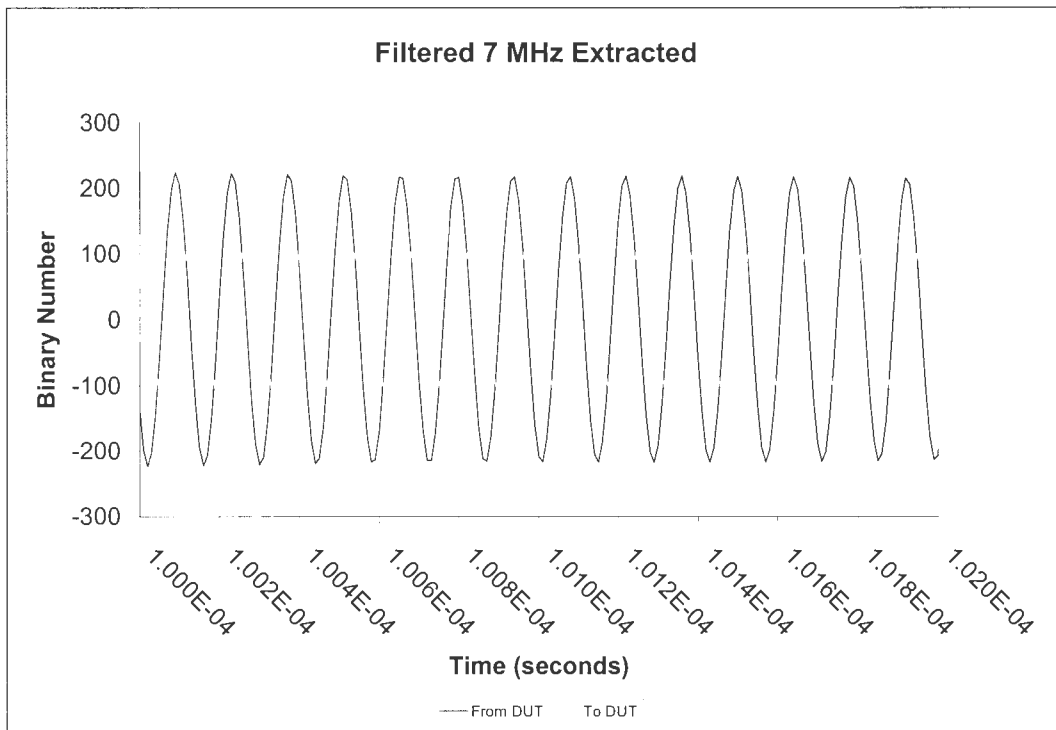


Figure 15. Filtered 7 MHz signal extracted from a multi-frequency signal containing all four frequencies.

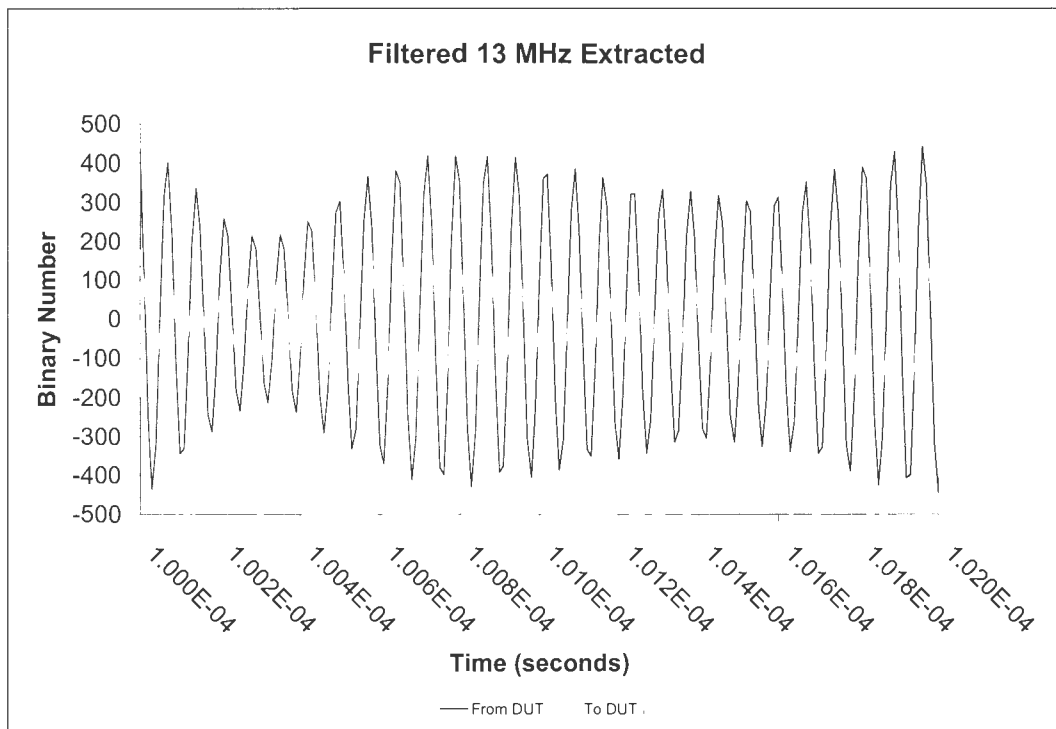


Figure 16. Filtered 13 MHz signal extracted from a multi-frequency signal containing all four frequencies.

The amplitude of sequential frequencies is approximately 4 times the amplitude of the same frequency extracted from a multi-frequency signal. This is expected with the data acquisition configuration for summing together four frequencies.

Conclusion

This study has shown frequencies extracted from a multi-frequency signal are capable of providing the same signal information as sequentially scanned frequencies. A previous study at Iowa State University has shown the determination of hay and forage moisture content prior to compaction was possible using impedance measurements of capacitive type sensors at multiple frequencies (Eubanks and Birrell, 2001). These impedance measurements were taken using sequential frequencies taking many seconds. In this study a multi-frequency signal made up from summing four frequencies took 0.0003268 seconds. A hay bale 91.44 cm long taking 10 seconds to make would only move 0.03 mm in the time required to acquire 339 cycles for 1 MHz, 766 cycles for 3 MHz, 2337 cycles for 7 MHz, and 4401 cycles for 13 MHz of unfiltered data. After filtering the signals moisture prediction is based on 277 cycles at 1 MHz, 766 cycles at 3 MHz, 1909 cycles at 7 MHz, and 3595 cycles at 13 MHz. These high numbers of cycles acquired for a bale moving 0.03 mm provides a sample rate which is above and beyond the requirements to be a real-time sensor.

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CHAPTER 3. EVALUATION OF A MULTI-FREQUENCY DIELECTRIC SENSING SYSTEM FOR REAL-TIME HAY MOISTURE MEASUREMENT

To be published as a journal article
in Transactions of the ASAE.

Abstract

A previous study at Iowa State University has shown promise for the determination of hay and forage moisture content prior to compaction using multi-frequency dielectric measurements. This previous study used a sensing system that took sequential frequency measurements which takes considerable time. This paper will report on the testing of the sensing hardware for “simultaneous” multi-frequency dielectric measurements and the evaluation of the system under static test conditions. Ideally, the measurement system will be capable of predicting the moisture content independent of density, material volume, and material composition.

The sensing system was tested at two different locations, Stardell Farms in Fredericksburg, Iowa, and the University of Wisconsin Arlington Research Station in Arlington, Wisconsin. Density independent moisture predictions were considerably better at Arlington with an adjusted R^2 equal to 0.80 with RMSE equal to 1.0 %MC wet basis for best sequential frequency combination 3 and 13 MHz. Arlington’s density independent moisture prediction has an adjusted R^2 equal to 0.79 with RMSE equal to 1.0 %MC wet basis for best extracted frequency combination of 3, 7, and 13 MHz. Stardell Farms yielded a density independent adjusted R^2 equal to 0.68 with RMSE equal to 7.4 %MC wet basis for best frequency combination of 7 MHz. The best extracted frequency combination of 3, 7, and 13 MHz yielded an adjusted R^2 equal to 0.67 with 7.5 %MC wet basis. At both locations the adjusted R^2 and RMSE was slightly higher for the sequential frequency combinations. At Stardell Farms the adjusted R^2 increased as the density increased while the adjusted R^2 remained approximately the same at Arlington regardless of density.

Introduction

Moisture content usually reflects the hay quality which affects the harvesting, storing, buying, and selling of hay and forage (Eubanks and Birrell, 2001). Harvesting high moisture hay can create spoilage and possibly internal bale combustion during storage. If hay is too dry during harvest lower quality hay is acquired because more leaves fall off due to the dry conditions. With hay marketed on a wet weight basis lower profits are achieved when hay is either too wet or too dry hay. Making adjustments based on alfalfa moisture content during harvest would optimize profits.

To successfully harvest and store wet hay a preservative needs to be added. If the crop mass flow rate and the moisture content are known then preservative application can be optimized. The most common hay preservative to reduce storage losses is propionic acid which reduces microbial growth and subsequent heating (Shinners, 2000).

Various methods to determine moisture content that are developed or being developed includes oven drying, electric meters, NIR spectroscopy, and dielectric measurements. The baseline for hay moisture measurement comparisons is oven drying using ASAE Standard S358.2 (ASAE, 2003). This standard requires a representative sample to be in the oven for 24 hours at 103 degrees Celsius or for 72 hours at 60 degrees Celsius. Electronic meters are currently the most widely used method commercially to determine hay and forage moisture content (Henson et al., 1987). NIR spectroscopy using microwave reflections and capacitive systems can also predict forage moisture content (Kormann and Auernhammer, 2002). Dielectric moisture measurement sensors have shown potential in the radio frequency range (Eubanks and Birrell, 2001). Many of the current moisture sensors available determine the moisture content after bale formation. These capacitive sensors operate at a single frequency making them sensitive to hay density. Many field calibrations are required to account for the varying bale density and ambient conditions.

For a number of years grain moisture sensors using capacitive type methods and other impedance measurements have been in widespread commercial use. The dielectric properties of several grains are specified in ASAE Standard D293.2 (ASAE, 1998). Measured impedance depends on both the moisture content and the bulk density of the sample. Many of these moisture sensors require field calibrations to account for the changes in sample density. The development of density-independent functions of the dielectric properties of grains has been and still is being investigated in both the radio and microwave frequency ranges (Gillay and Funk, 2003; Nelson and Trabelsi, 2002). It was also found that dielectric constants vary according to temperature and frequency for grains (Nelson, 2003).

A previous study at Iowa State University has shown the determination of hay and forage moisture content prior to compaction was possible using impedance measurements of capacitive type sensors at multiple frequencies (Eubanks and Birrell, 2001). Impedance measurements of each sample were taken at sequential frequencies from 5 Hz to 13 MHz. A multiple linear regression to predict moisture content was used to obtain an equation utilizing multiple frequencies. The correlation between actual and predicted moisture content increased as the number of frequencies in the model increased. For density independent alfalfa moisture predictions, $R^2 = 0.2249$ using the best single frequency. Using additional frequencies R^2 increases as follows: $R^2 = 0.7163$ for 2 frequencies, $R^2 = 0.7758$ for 3 frequencies, $R^2 = 0.8538$ for 4 frequencies, and $R^2 = 0.9532$ for 5 frequencies (Eubanks and Birrell, 2001). It takes many seconds to record a multi-frequency measurement using the sequential frequency method. A real-time moisture sensor has to be capable of predicting moisture at the speed which material flows through the machine. A real-time sensor does not have many seconds to take a measurement. Large amounts of material will have passed through the sensing volume in a few seconds. The first frequency may measure one sample mass and the final frequency may measure an entirely different sample mass. Taking multi-frequency dielectric measurements simultaneously would ensure all measurements are from the same sample mass. This would minimize the variable material flow effects on moisture prediction.

Objectives

The objective is to evaluate the predictive ability of sensor hardware developed for a real-time hay moisture sensing system. The sensor hardware under test has been discussed in detail in previous paper (Benning et al., 2004). The ideal moisture sensor would be capable of predicting real-time moisture for a wide moisture content range. Specific objectives include:

- 1) Determine if sequentially scanned frequencies predict hay moisture content better than frequencies extracted from a multiple frequency signal.
- 2) Evaluate both low and high moisture alfalfa to determine which is better at predicting hay moisture contents.

Apparatus

Based on a previous study performed at Iowa State University four frequencies were chosen and are 1 MHz, 3 MHz, 7 MHz, and 13 MHz (Eubanks and Birrell, 2001). These four frequencies were measured sequentially and also extracted and measured from a multiple frequency signal containing all four frequencies. This paper will report on the evaluation of the sensing hardware for “simultaneous” multi-frequency dielectric measurements that has been developed.

The dielectric impedance measurements were based on auto-balancing bridge measurement techniques, which is the standard method of measuring impedance at frequencies less than 40 MHz (Agilent Technologies, 2003). A simplified schematic of the electronic measurement circuit is shown in Figure 1. The transconductance amplifiers on the left sum the inputs from up to four sinusoidal signals at multiple frequencies. The buffer OP-AMP 1 provides the input voltage to the DUT, resulting in the current flow through the DUT. The current is inversely proportional to the complex impedance of the DUT. The operational amplifier OP-AMP 3, forms an auto-balancing bridge circuit. If the response of the OP-AMP 3 is assumed to be ideal, the inverting and non-inverting inputs will be maintained at the same voltage, unless the OP-AMP is saturated. The non-inverting input of OP-AMP 3 is connected to ground, therefore the inverting input of OP-AMP 3 is a virtual ground. Assuming that the

input impedance of the inverting input of the OP-OMP is infinite, the current flowing across resistor R_3 is the same as that through the DUT. Therefore, the output signal of OP-AMP 3 V_3 is directly proportional to the current flow through the DUT. The additional OP-AMPS 2,4,5 provide buffered inputs to the guard plate and A/D converter. In this study, the DUT represents a parallel sensor plates with hay as the dielectric medium. A full description of the system is given in Benning et al., 2004.

The sensor plates were developed, fabricated, and used at both test sites. Each sensor plate was insulated and contained both sensing and guarding areas as shown in Figure 2. The sensing area was 297.3 cm^2 and the guard area was 305.0 cm^2 . The distance between the plates was 49.6 cm at Stardell Farms and 36.8 cm at Arlington

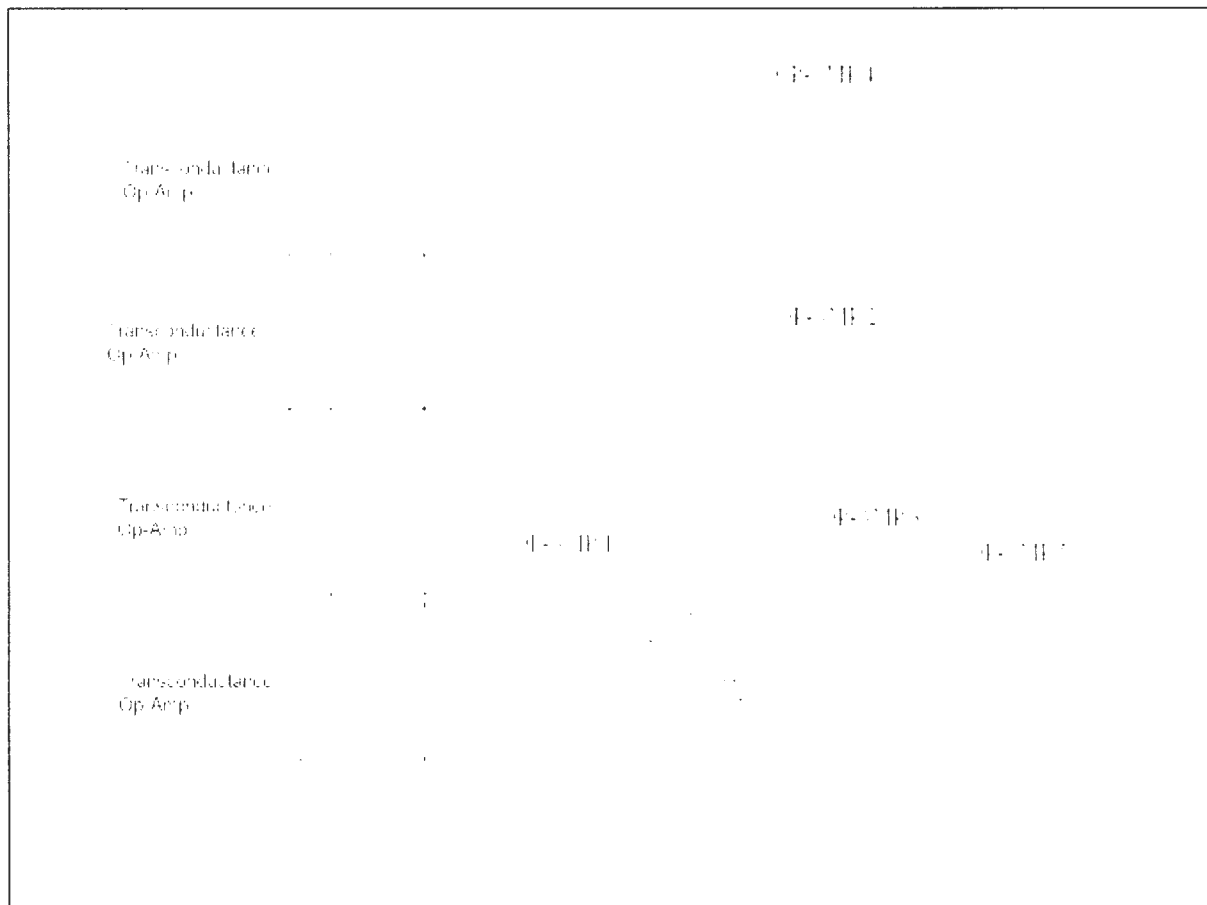


Figure 1. Schematic of auto-balancing bridge sensor circuit with buffer operational amplifier drivers for the sensing signal, guard signal, and buffered data acquisition signals.

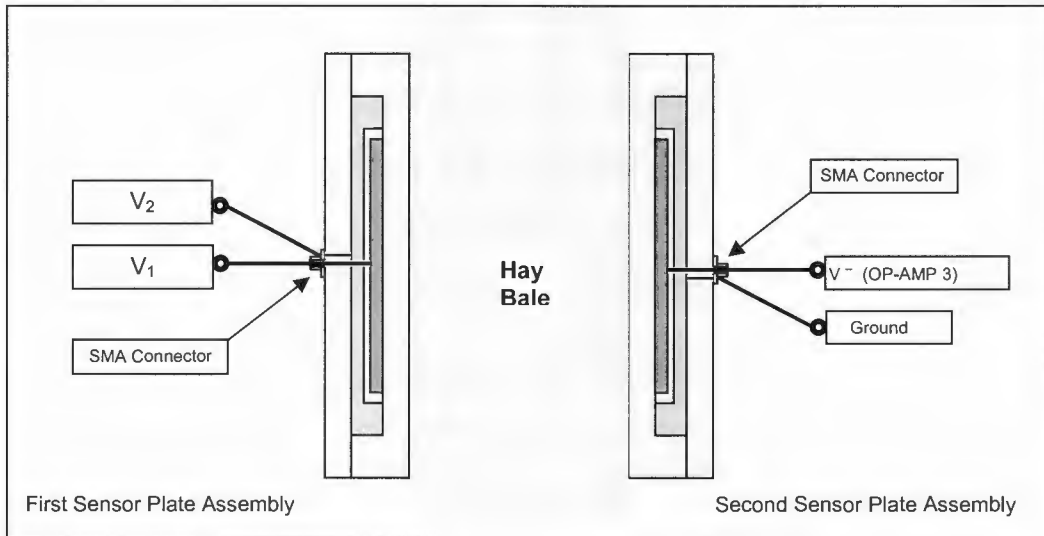


Figure 2. Cross sectional view of the sensor plate configuration showing the sensor plates (in red), acrylic insulators (in blue) and guard plates (in orange).

The sensor plates were held in position at Stardell Farms with a steel backing 19 cm thick that bolted to steel tube supports. The steel tube supports were clamped to a table top so a bale could be placed with the strings down between the sensor plates as shown in Figure 3. At Arlington the sensor plates were held in position using the same 19 cm thick steel backing used at Stardell Farms. Only the steel backing was bolted to a fabricated bale chamber where the bales were oriented with the strings on their side. In figure 4, the grey sensor steel backing plate is shown installed in the fabricated bale chamber used at Arlington.

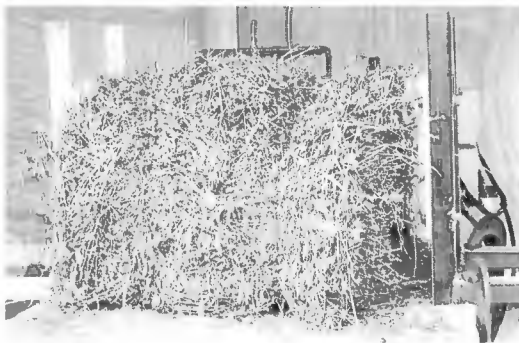


Figure 3. Stardell Farms bale chamber.



Figure 4. Loading bale into fabricated bale chamber at Arlington Research Station.

Stardell Farms Testing

Testing was conducted at Stardell Farms in Fredericksburg, Iowa. The baled crop was the second cutting of three year alfalfa variety Dairyland Magnum 5. Bales were made using sisal twine with a small square baler (Model 338, John Deere) pulled by a 130 Hp, 2WD tractor (John Deere 4320). Typical ground speed ranged from 2 to 3 mph with the tractor engine speed at PTO speed. The baler was adjusted to achieve three different bales densities which are low, medium, and high densities. The medium density setting was the typical bale compaction chamber setting for this farm. The low setting was achieved by loosening the bale compaction chamber 6 turns from the medium setting. The high setting was achieved by tightening the bale compaction chamber 6 turns from the medium setting. Density settings were randomly selected for each baling run and initial bales formed after a density change were not collected. A baling run consisted of collecting a total of 15 sample bales with 5 sample bales from each of the 3 density settings. The five sample bales were randomly selected from 20 bales made at each density setting. A total of seven baling runs were done over three days with all runs approximately starting at 12:01 pm, 3:00 pm, or 6:00 pm for an overall total of 105 sample bales.

The dielectric measurements were recorded with cur edge of the bale in contact with the sensor plates. A Visual Basic program (version 6.0, Microsoft, Redmond, WA) collected dielectric measurements from all 15 frequency combinations. After collecting dielectric measurements on the bale its dimensions and weight were recorded. Three independent moisture content samples (30g minimum), consisting of at least three randomly spaced 25 mm diameter cores, were taken for each bale. The collected samples were stored in metal cans, and the moisture content determined according the ASAE forage moisture standard S358.2 (ASAE, 2003). The samples were dried at 103 degrees Celsius for 24 hours.

Arlington Research Station Testing

Alfalfa was baled on five different fields and all were second year crops. Bales were made using sisal twine with a small square baler (Model 575, New Holland) pulled by a 170 Hp, 2WD tractor (Case MX170). Typical ground speed ranged from 2 to 3 mph with the tractor engine speed at 1300 to 1500 rpm. Bales were made 7 times (7 runs) during 6 days of testing. The baling times were between 12:30pm to 5:35pm according to the current alfalfa moisture content. Alfalfa baled for two of the runs had some to all of the color washed out.

Each baling run consisted of making 10 consecutive bales, and testing conducted on the test stand at central location. A bale being loaded into the test cell is shown in Figure 4. After loading bale the chamber top was squeezed down onto bale cut edge leaving the bale top and bottom in contact with the sensor plates. Moisture prediction measurements were taken at three different bale densities and acquired by squeezing each bale lengthwise with a plunger to achieve a desired density between sensor plates. Each bale had a low, medium, and high density measurement taken in that order. The average low density moisture measurement was at 174.7 kg/m^3 . The average medium density moisture measurement was at 183.4 kg/m^3 and the average high density moisture measurement was at 214.2 kg/m^3 .

After taking the moisture prediction measurements at three densities, the bale weight was recorded. Next, three zone moisture samples, consisting of 5 to 6 cores were taken from the bale cut side. The 102mm (4 inch) diameter drilling whole saw removed a depth into the bale consisting of most of its diameter. Each sample was mixed and a portion was put into a paper bag. The paper bag was weighed before any material was put into it. After filling the bag with material it was weighed again to find the sample wet mass. A coring tool mounted on the back of a John Deere 7820 was used to obtain an additional core sample through the entire bale length. Coring tube inside diameter was 51mm (2 inches) and 63.5 cm (25 inches) long. Collected moisture samples were stored in paper bags and transported to University of Wisconsin Agricultural Engineering lab where they were processed according the ASAE forage moisture standard S358.2 being dried at 103 degrees Celsius for 24 hours (ASAE, 2003).

Analysis

For both testing sites the moisture content was predicted from the sine wave attenuation of the chosen frequencies. Before computing attenuation raw data files were filtered in Matlab to separate the individual frequencies. Bandpass FIR Equiripple filters were used with the limits specified in Table 1.

Table 1. Matlab Bandpass FIR Equiripple filter parameters.

| Filter Parameters | Nominal Frequency | | | |
|---------------------------|-------------------|--------|--------|---------|
| | 1 MHz | 3 MHz | 7 MHz | 13 MHz |
| Passband Center Frequency | 1.035 | 2.863 | 7.132 | 13.431 |
| Low Stop Band Frequency | 0.91 | 2.738 | 7.013 | 12.211 |
| Low Pass Band Frequency | 0.9725 | 2.8001 | 7.0755 | 12.2735 |
| High Pass Band Frequency | 1.035 | 2.9255 | 7.2005 | 14.3985 |
| High Stop Band Frequency | 1.0975 | 2.988 | 7.263 | 14.461 |

The filtered signals were imported into JMP to determine the signal amplitudes. JMP is a statistical program developed by SAS. The amplitude of the sine wave was determined by multiplying V_{RMS} by the square root of two. Theoretically, the V_{RMS} of a continuous sine wave is equivalent to the digital wave's standard deviation of all data points in the signal. The number of wave cycles used to calculate amplitude varied according to the input frequency. The standard deviation was calculated from 277 cycles for 1 MHz, 766 cycles for 3 MHz, 1909 cycles for 7 MHz, and 3595 cycles for 13 MHz. The attenuation was determined by dividing the signal output amplitude by the signal input amplitude for each frequency combination.

A curvilinear trend was found when plotting attenuation versus actual %MC wet basis. The curvilinear trend became linear after a data transformation where the natural log was taken for both the attenuation and the actual %MC wet basis. This transformation allowed a multiple linear regression equation to be fitted to the data using JMP, for each sequential and extracted frequency combination. The estimated parameter coefficients for the statistical model based on the log transforms, were then used to predict sample moisture content from for each frequency combination. The adjusted R^2 and root mean square errors, RMSE, shown are based on a comparison of predicted versus actual data.

Results and Discussion

Stardell Farms The minimum individual bale moisture was 20.8 percent and the maximum moisture was 79.5 percent. The ambient temperature and humidity were recorded during every bale measurement with a Fisher Scientific digital humidity and temperature meter. The average temperature during testing was 26.2 degrees Celsius with a standard deviation of 5.1 degrees. The average relative humidity during testing was 40.7 percent with a standard deviation of 7.0 percent.

The average moisture content of the three sampling containers for each bale was used to represent the moisture content of the material being measured. The average bulk density and actual average bale moisture content were determined for each run according to bale density and are shown in Table 2 with their standard deviations. Both the actual moisture contents and bulk density show an expected decreasing trend because the hay was drying over time. Due to field conditions, run 7 increased in both the %MC wet basis and the bulk density.

Table 2. Density dependent mean bulk density with its standard deviation and mean %MC wet basis with its standard deviation of all bales tested in each run at Stardell Farms.

| | Mean Bulk Density (Std. Dev.), [kg/m ³] | | | Mean Moisture Content (Std. Dev.), [%MC] | | |
|--------------|---|--------------|--------------|--|------------|------------|
| | Nominal Bale Density | | | Nominal Bale Density | | |
| | High | Medium | Low | High | Medium | Low |
| RUN 1 | 218.9 (24.2) | 215.5 (28.0) | 249.0 (52.6) | 72.7 (3.6) | 71.2 (5.0) | 71.1 (3.4) |
| RUN 2 | 220.4 (26.6) | 205.2 (13.0) | 171.4 (14.3) | 73.0 (4.1) | 67.7 (3.3) | 70.1 (4.7) |
| RUN 3 | 184.9 (13.9) | 166.0 (13.0) | 176.2 (36.3) | 57.2 (6.3) | 55.4 (3.0) | 62.3 (1.6) |
| RUN 4 | 202.3 (10.6) | 184.8 (25.0) | 146.2 (4.6) | 74.5 (2.6) | 69.0 (3.6) | 66.3 (5.1) |
| RUN 5 | 145.0 (15.2) | 131.9 (7.0) | 143.8 (21.9) | 56.9 (2.0) | 57.5 (1.8) | 58.4 (4.1) |
| RUN 6 | 108.6 (22.6) | 97.0 (15.6) | 109.0 (6.7) | 35.1 (10.6) | 39.8 (4.3) | 37.7 (7.6) |
| RUN 7 | 219.4 (13.5) | 172.4 (24.0) | 139.1 (14.2) | 48.1 (1.3) | 46.1 (4.6) | 45.7 (5.0) |

Sequential frequency attenuations versus the actual %MC wet basis are shown in Figure 5 with a regression line for each frequency. Frequencies 1 MHz, 3 MHz, and 7 MHz have similar slopes but 13 MHz was noticeably different.

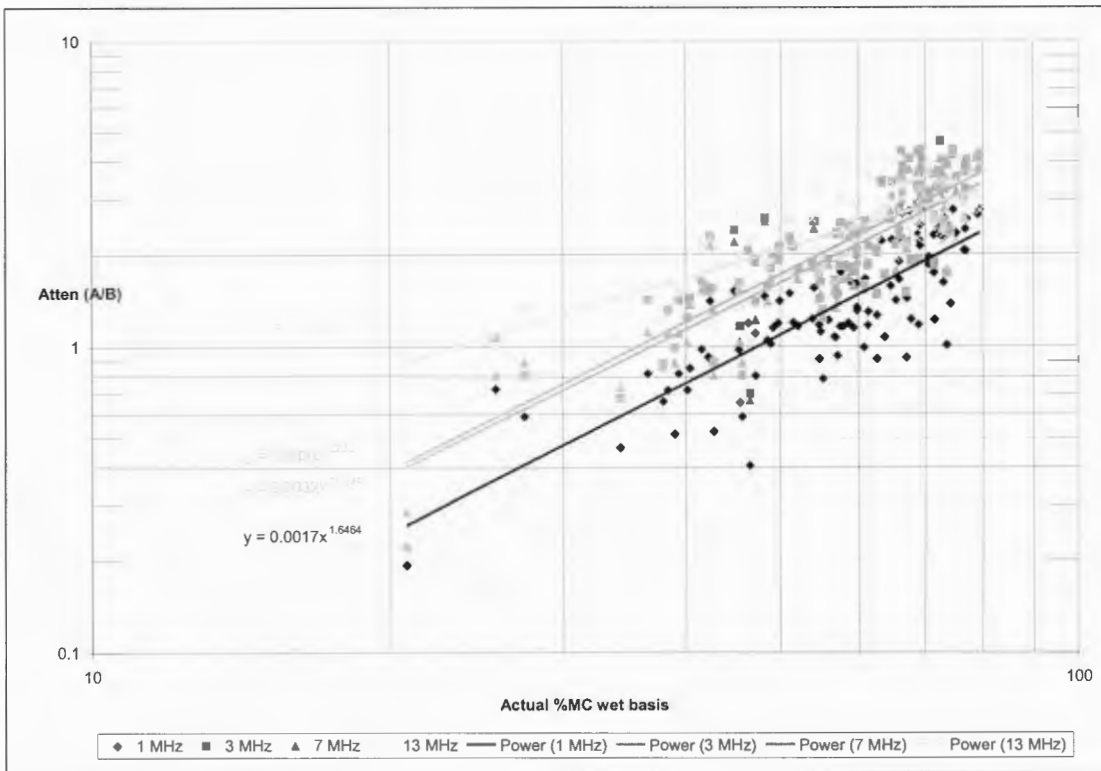


Figure 5. Density independent attenuation vs. actual %MC wet basis for each sequential frequency at Stardell Farms.

Density independent %MC wet basis predictions are shown in Table 3 for best single and multiple frequency combinations. A stepwise regression was performed in JMP utilizing all four sequential frequency attenuations. The best moisture prediction combination for sequential frequencies was using only the 7 MHz frequency yielding an adjusted $R^2 = 0.68$ with $RMSE = 7.4$ %MC wet basis.

A simultaneous signal made up of all four frequencies was also used to predict % MC wet basis. Extracted frequency attenuations were acquired by filtering the simultaneous signal. Regression lines were made for each extracted frequency and this comparison is shown in Figure 6. All regression lines showed an increasing slope. The best extracted frequency combination was determined in JMP using stepwise linear regression and found to be the frequency combination of 7 MHz and 13 MHz with adjusted $R^2 = 0.67$ and $RMSE = 7.5$ %MC wet basis as found in Table 3.

Table 3. Density independent moisture prediction comparing sequential and extracted frequency combinations at Stardell Farms (Optimum combination in bold).

| Frequency Combinations | Sequential Frequencies | | Extracted Frequencies | |
|------------------------|------------------------|------------|-----------------------|------------|
| | adj-R ² | RMSE | adj-R ² | RMSE |
| 1 MHz | 0.65 | 7.8 | 0.63 | 8.0 |
| 3 MHz | 0.65 | 7.7 | 0.64 | 7.8 |
| 7 MHz | 0.68 | 7.4 | 0.64 | 7.9 |
| 13 MHz | 0.44 | 9.8 | 0.49 | 9.3 |
| 7 MHz, 13 MHz | | | 0.67 | 7.5 |

The slope of 13 MHz was similar for both the sequential and extracted frequency combinations. When the prediction results of the extracted measurements were compared to those for the sequential measurements, for the 1 MHz, 3 MHz, and 7 MHz the adjusted R² values for the extracted measurements were 0.01 to 0.04 lower than for the sequential frequency method. These frequencies also had an increase in the root mean square error, RMSE, from 0.1 to 0.5 %MC wet basis. The extracted 13 MHz adjusted R² value increased

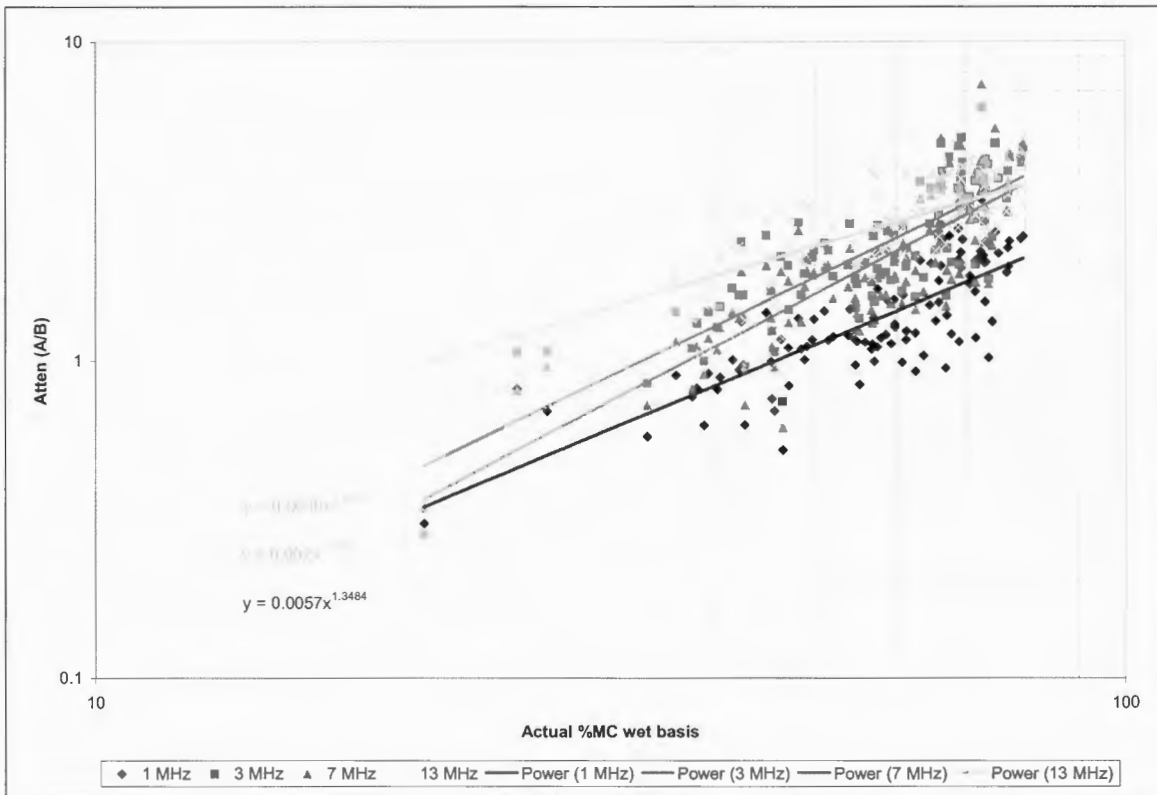


Figure 6. Density independent attenuation vs. actual %MC wet basis of each extracted frequency filtered from a signal containing all frequencies at Stardell Farms.

0.05 from the sequential combination which is the opposite of the other three frequencies.

The RMSE decreased 0.5 %MC wet basis for an extracted 13 MHz which is also the opposite direction from the other three frequencies.

The density dependence and independence for both sequential and extracted frequency combinations are compared in Table 4. The adjusted R^2 increased as the density increased in both sequential and extracted frequency combinations. This is to be expected since higher density samples have more material in the sensing volume, and therefore it is logical that higher densities were better at predicting entire bale moisture. Density independent adjusted R^2 values were better than the low density predictions.

Table 4. Moisture predictions using the best frequency combinations at Stardell Farms. Best sequential frequencies include 7 MHz while best extracted frequencies include 7 and 13 MHz.

| | Prediction Results by Nominal Density | | | | | | | |
|-------------------|---------------------------------------|------|------------|------|------------|------|------------|------|
| | Independent | | Low | | Medium | | High | |
| | adj- R^2 | RMSE | adj- R^2 | RMSE | adj- R^2 | RMSE | adj- R^2 | RMSE |
| Sequential | 0.68 | 7.4 | 0.53 | 8.7 | 0.71 | 6.3 | 0.77 | 7.2 |
| Extracted | 0.67 | 7.5 | 0.56 | 8.4 | 0.70 | 6.5 | 0.72 | 7.9 |

An ideal moisture prediction equation would show a slope of one when plotting predicted moisture content versus the actual moisture content. The slope obtained from the best sequential combination has a slope of 0.73 and the best extracted combination has a slope of 0.71 as shown in Figure 7. In the case where extracted frequencies are equally as accurate as sequential frequencies, the prediction points of both methods should overlap and not appear as two separate points.

Individual sample cores for the standard tests, had an RMSE of 5.8 %MC wet basis when compared to the average moisture content for each bale. Therefore, a significant portion of the moisture prediction RMSE could be a result of the standard tests not being truly representative of the hay within the sensor volume. The difference in standard moisture content measurements between repeated samples from the same bale are due to heterogeneity within the bale. Therefore, a considerable portion of the prediction error may be due to sampling variability between the standard samples and the bale volume being measured.

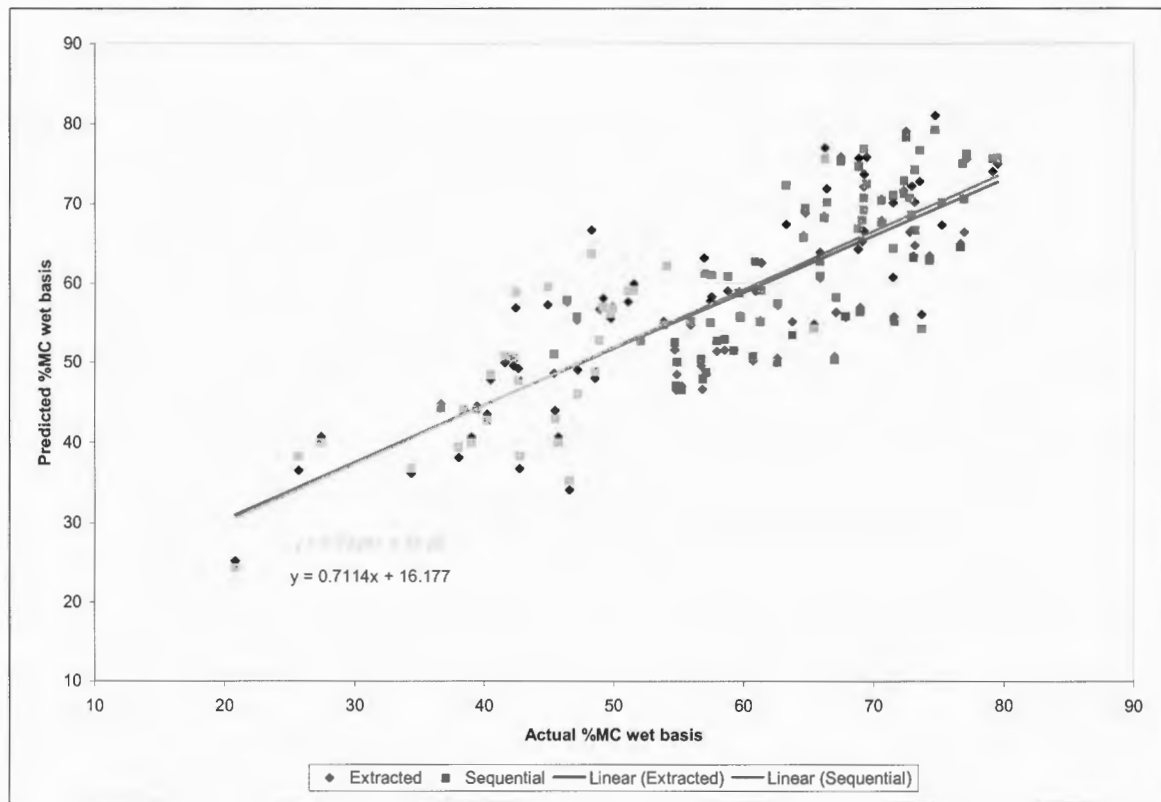


Figure 7. Density independent predicted vs. actual %MC wet basis for best sequential and extracted frequency combinations at Stardell Farms.

Arlington Research Station The maximum bale core moisture was 23.2 percent and the minimum bale core moisture was 15.7 percent. The average temperature during testing was 76.2 degrees Fahrenheit with a standard deviation of 6.3 degrees. The average relative humidity was 52.3 percent with a standard deviation of 12.9 percent. Both temperature and humidity were recorded during every bale measurement with a Fisher Scientific digital humidity and temperature meter.

The bale core represents the standard bale moisture content. The mean bulk density and moisture content each for each run are shown in Table 5. A general trend exists between the moisture content and the bulk density where decreasing moisture contents have decreasing bulk densities. Unfortunately, the data for the run 3 at medium and high density, was found to be significantly different from the rest of the data and therefore these outliers were removed from the analysis.

Table 5. Density dependent mean bulk density with its standard deviation and mean %MC wet basis with its standard deviation of all bales tested in each run at Arlington.

| | Mean Bulk Density (Std Dev), kg/m ³ | | | Mean % MC (Std. Dev.), %MC wet basis | | | |
|-------|--|--------------|--------------|--------------------------------------|------------|------------|------------|
| | High | Medium | Low | Core | Zone1 | Zone2 | Zone3 |
| Run 1 | 195.2 (16.9) | 169.3 (12.9) | 149.4 (12.6) | 16.8 (0.4) | 17.0 (0.8) | 16.8 (0.6) | 16.8 (0.8) |
| Run 2 | 235.7 (17.7) | 201.1 (14.7) | 177.0 (11.7) | 20.8 (1.6) | 22.8 (2.1) | 23.8 (2.6) | 23.5 (1.9) |
| Run 3 | | | 257.9 (15.0) | 24.2 (1.3) | 24.2 (1.9) | 24.7 (1.7) | 24.2 (1.4) |
| Run 4 | 262.1 (25.5) | 229.0 (26.6) | 203.7 (25.2) | 26.5 (4.2) | 25.9 (3.7) | 25.5 (2.5) | 27.1 (4.9) |
| Run 5 | 190.7 (11.4) | 166.1 (9.0) | 146.5 (8.2) | 18.8 (1.7) | 19.3 (2.1) | 19.3 (1.5) | 19.5 (1.3) |
| Run 6 | 187.5 (13.9) | 155.4 (10.9) | 132.8 (9.7) | 16.4 (0.7) | 16.9 (0.9) | 16.6 (0.7) | 16.6 (0.7) |
| Run 7 | 214.1 (14.7) | 179.6 (10.9) | 155.3 (10.0) | 18.4 (1.0) | 20.5 (1.3) | 20.0 (0.8) | 20.0 (1.8) |

Sequential frequency attenuations versus actual moisture content are shown in Figure 8 on a log-log scale with a regression line for each frequency. The regression slopes for 1 MHz, 3 MHz, and 7 MHz signals increased with moisture content, whereas the 13 MHz signal was the opposite.

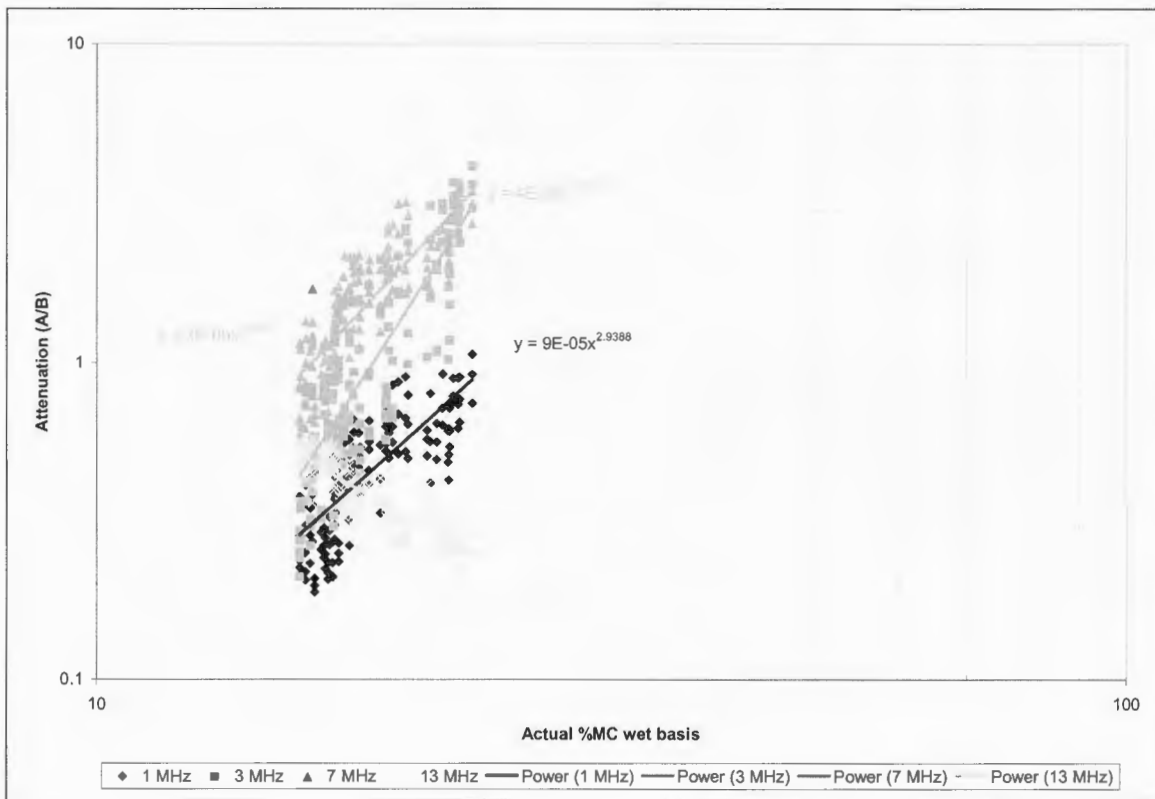


Figure 8. Density independent attenuation vs. core %MC wet basis for each sequential frequency at Arlington.

A multiple linear regression in JMP was used to develop prediction parameters from the log transformed data. The results of density independent %MC wet basis predictions for single frequencies and best multiple frequency combinations are shown in table 6. The best sequential multiple frequency combination predicting %MC wet basis is the combination of 3 and 13 MHz frequencies yielding an adjusted R^2 equal to 0.80 with RMSE equal to 1.0 %MC wet basis. The best extracted multiple frequency combination predicting %MC wet basis is the combination of the 3, 7 and 13 MHz frequency signals yielding an adjusted R^2 equal to 0.79 with RMSE equal to 1.0 %MC wet basis.

Table 6. Density independent moisture prediction comparing sequential and extracted frequency combinations at Arlington.

| Model Frequencies (MHz) | Sequential | | Extracted | |
|------------------------------------|-----------------------------|-------------|-----------------------------|-------------|
| | adj-R^2 | RMSE | adj-R^2 | RMSE |
| 1 | 0.60 | 1.4 | 0.71 | 1.1 |
| 3 | 0.66 | 1.3 | 0.66 | 1.3 |
| 7 | 0.71 | 1.2 | 0.73 | 1.1 |
| 13 | 0.71 | 1.1 | 0.27 | 1.8 |
| 3, 13 | 0.80 | 1.0 | | |
| 7, 13 | | | 0.74 | 1.1 |
| 3, 7, 13 | | | 0.79 | 1.0 |
| Best Combo | 0.80 | 1.0 | 0.79 | 1.0 |

Extracted frequency attenuations obtained by filtering the simultaneous signals were compared to the moisture content of the hay bale. Regression lines made for each extracted frequency are shown in Figure 9 on a log-log scale. The 13 MHz regression line for sequential frequencies has an increasing slope, but has a decreasing slope for extracted frequencies. The other three frequencies have an increasing slope for both sequential and extracted frequencies.

The different zone samples, had an RMSE of 1.2 %MC wet basis when compared to the Core moisture content and a significant portion of the moisture prediction RMSE could be a result of the standard tests not being truly representative of the hay within the sensor volume. In this data set the sensor prediction RMSE (1.0 %MC) is actually lower than the RMSE (1.2 %MCs) went predicting the standard Core moisture content from the three standard zone moisture samples. Therefore, the sensor prediction error is less than the sampling error

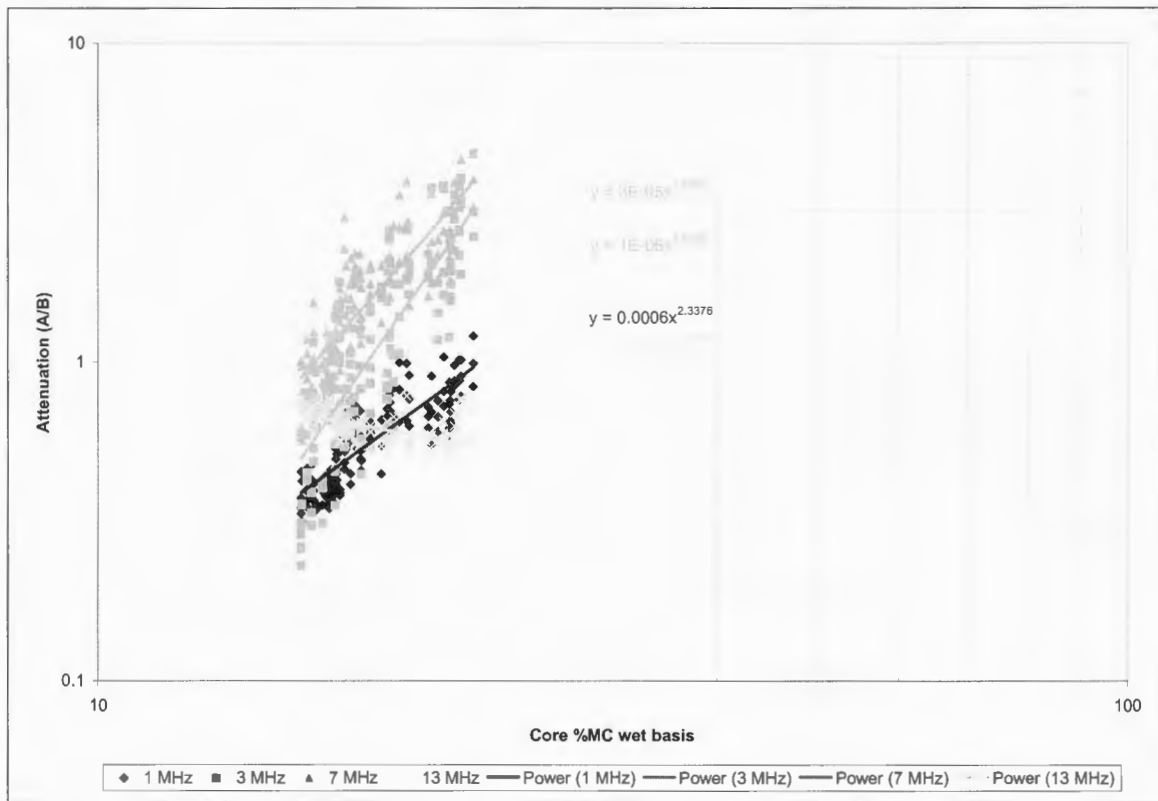


Figure 9. Density independent attenuation vs. core %MC wet basis for each extracted frequency filtered from a signal containing all frequencies at Arlington.

The density dependence and independence for predicting moisture is compared in Table 7 for both sequential and extracted frequency combinations. Both the sequential and extracted frequency combinations should yield similar density independent adjusted R^2 values but some of the sequential signals were saturated. Similar adjusted R^2 values were found at all densities for both the sequential and extracted frequency combinations. For density independent moisture predictions the sequential frequency combination yielded an adjusted R^2 value 0.01 better than the extracted frequency combination.

Table 7. Moisture predictions using the best frequency combinations at Arlington. Sequential uses best frequency combination of 3 and 13 MHz. Extracted uses best frequency combination of 3, 7, and 13 MHz.

| | Prediction Results by Nominal Density | | | | | | | |
|-------------------|---------------------------------------|------|------------|------|------------|------|------------|------|
| | Independent | | Low | | Medium | | High | |
| | adj- R^2 | RMSE | adj- R^2 | RMSE | adj- R^2 | RMSE | adj- R^2 | RMSE |
| Sequential | 0.80 | 1.0 | 0.82 | 0.9 | 0.84 | 0.8 | 0.82 | 0.9 |
| Extracted | 0.79 | 1.0 | 0.82 | 0.9 | 0.83 | 0.9 | 0.83 | 0.9 |

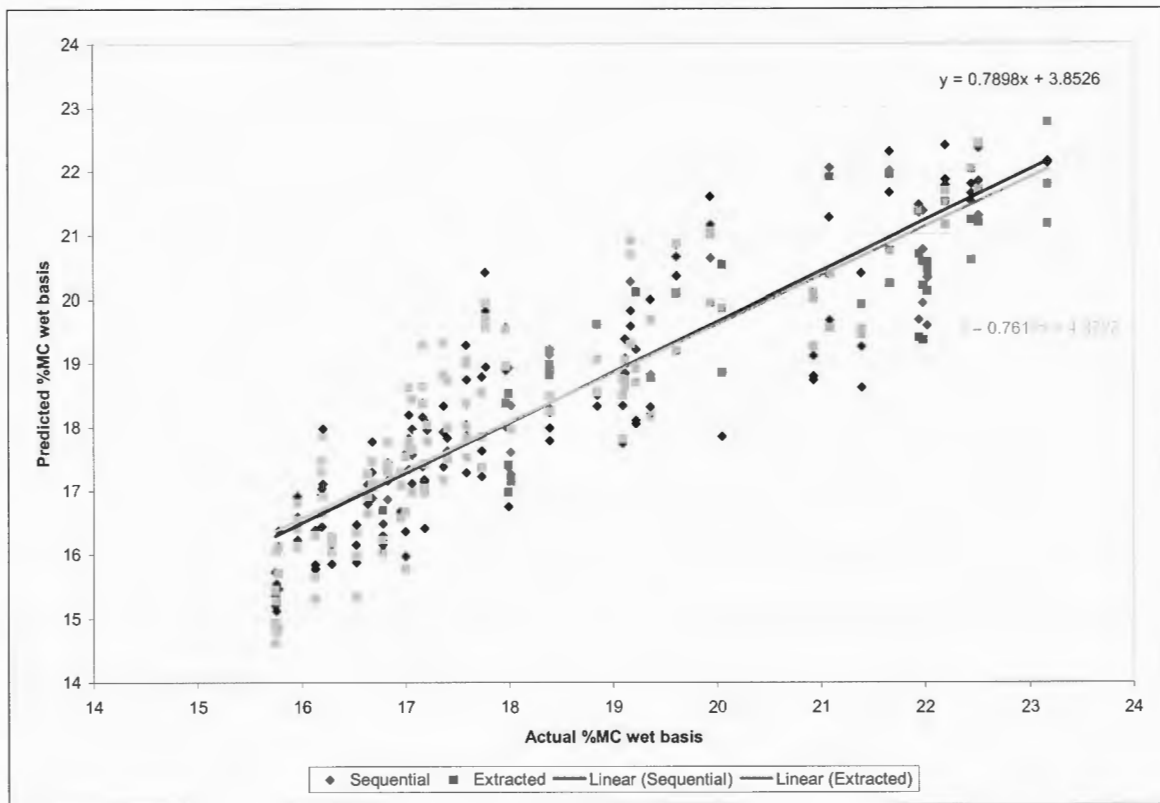


Figure 10. Density independent predicted vs. core %MC wet basis for best sequential and extracted frequency combinations at Arlington. Best sequential frequencies include 3 and 13 MHz while best extracted frequencies include 3, 7, and 13 MHz.

A potential source of error between Stardell Farms and Arlington involves the timing for drying the samples and the moisture variation for bale samples. At Stardell Farms samples were dried 1 to 4 days after being collected while at Arlington samples starting drying the same day. This sample drying timing may be a reason why Stardell Farms had the RMSE of 5.8 %MC wet basis for hand sampling which makes up three quarters of the prediction error found. While Arlington only had an RMSE of 1.2 % MC wet basis for hand sampling which is greater than the prediction error found.

Conclusion

Alfalfa moisture prediction tests were performed at two geographic locations. One location was Stardell Farms in Fredericksburg, Iowa and the other location was the Arlington Research Station near Madison, Wisconsin. The alfalfa moisture contents tested were higher at Stardell Farms than at Arlington. Alfalfa ranged from an average of 35.1 to 74.5 percent moisture content wet basis (%MC wet basis) at Stardell Farms. At Arlington alfalfa ranged from a run average of 16.4 to 26.5 %MC wet basis. Higher prediction accuracies found at the Arlington, suggesting that this moisture prediction system worked better in the lower moisture range. The Arlington plate separation distance was only 36.8 cm compared to the 49.6 cm at Stardell Farms which may be a factor why the moisture prediction accuracy was better at Arlington. Another difference between locations is that the same bale was tested at all three densities at Arlington and entirely different bales for each density were used at Stardell Farms.

For testing performed at Stardell Farms the density independent sequential frequency combinations predicted hay moisture with an adjusted R^2 equal to 0.68 with RMSE equal to 7.4 %MC wet basis. The extracted frequencies had an adjusted R^2 equal to 0.67 with RMSE equal to 7.5 %MC wet basis. Testing performed at Arlington yielded an adjusted R^2 equal to 0.80 with RMSE equal to 1.0 %MC wet basis for the best density independent sequential frequency combination. The best density independent extracted frequency combination at Madison yielded an adjusted R^2 equal to 0.79 with RMSE equal to 1.0 %MC wet basis. The best sequential combination used only 7 MHz at Stardell Farms and the combination of 3 MHz and 13 MHz at Madison. The best extracted frequency combination at Stardell farms is 7 MHz and 13 MHz, but found to be the combination of 3 MHz, 7 MHz, and 13 MHz for Arlington.

Density independent alfalfa moisture predictions at Stardell Farms were better than known low density measurements, but not as good as known high density measurements. Arlington density independent moisture predictions were comparable to density dependent moisture predictions. Moisture prediction tests performed at the Arlington Research Station had

considerably better prediction results over Stardell Farms moisture prediction. The density independent adjusted R^2 values were 0.12 higher and the RMSE was 6.4 to 6.5 %MC wet basis lower at Arlington. Variables between the locations include length of time between collecting and drying samples, bale orientation, sensor plate separation distance, sensor plate surroundings, time of the year, and sensor calibration bale coring method.

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CHAPTER 4. GENERAL CONCLUSIONS

General Discussion

Sensor hardware was developed and evaluated for real time prediction of alfalfa moisture content. The objective was to develop a system capable of measuring the dielectric properties of the same hay material at a number of frequencies. Assuming the average bale length is 91.44 cm (36 inches) and it takes 10 seconds to make one bale. This allows the entire sensing area to be in contact with the bale for 8.1 seconds. The sensor system required 0.0003268 seconds to collect a single data scan. During this time the hay bale will travel 0.03 mm showing this sensor, therefore all measurements are essentially from the same forage mass. If this data is processed within 1 second, and 8 cycles repeated for each bale, then the average predicted bale moisture is based on 2244 cycles for the 1 MHz signal, 6207 cycles for the 3 MHz signal, 15463 cycles for the 7 MHz signal, and 29121 cycles for the 13 MHz signal. Provided the prediction model is not biased, this provides an opportunity to take the average of multiple estimates, thereby increasing the prediction accuracy of the mean bale moisture content.

Alfalfa moisture prediction tests were performed at two geographic locations. One location was Stardell Farms in Fredericksburg, Iowa and the other location was the Arlington Research Station near Madison, Wisconsin. For testing performed at Stardell Farms the density independent sequential frequency combinations predicted hay moisture with an adjusted R^2 equal to 0.68 with RMSE equal to 7.4 %MC wet basis. The extracted frequencies had an adjusted R^2 equal to 0.67 with RMSE equal to 7.5 %MC wet basis. Testing performed at Arlington yielded an adjusted R^2 equal to 0.80 with RMSE equal to 1.0 %MC wet basis for the best density independent sequential frequency combination. The best density independent extracted frequency combination at Madison yielded an adjusted R^2 equal to 0.79 with RMSE equal to 1.0 %MC wet basis. The best sequential combination used only 7 MHz at Stardell Farms and the combination of 3 MHz and 13 MHz at Madison. The best extracted frequency combination at Stardell farms is 7 MHz and 13 MHz, but found to be the combination of 3 MHz, 7 MHz, and 13 MHz for Arlington.

Recommendations for Future Research

The multiple frequency method of predicting hay moisture content may be improved by further investigating a number of items. These items include: characterizing the cell, determining transmission line losses, circuit board modifications, oscillator chip affects, and the 13 MHz signal amplitude modulation.

Moisture prediction accuracy could be increased by characterizing the sensing cell. The ratio of sensing area to guarding area needs to be studied along with the ratio's relationship to sensor plate separation distances. Also, determine if the guard area around the sensor plate perimeter and on the back side of the sensor plate is beneficial. This can be tested using a known material to prove theoretical equations.

Understanding transmission line losses and taking corrective action should help clean up the noise found on the signals. In this study the guard signal was driven on the outside of the same cable which was driving the sensing signal. If the guard signal had its own cable connecting the guard plate to the circuit boards the noise may have been reduced. Circuit boards need to be redesigned to reduce the signal noise. Ground and power supply traces carried noise degrading the moisture prediction accuracy. Optimizing trace widths and possibly implementing ground planes should reduce noise levels. In addition the circuit board header may have introduced unwanted noise. For the next design iteration it may be beneficial to contain the entire circuit on one board. Another circuitry item to investigate is the resistor currently in series with the DUT connecting to the auto-balancing bridge. How does the size or presence of this resistor influence the moisture prediction accuracy?

Another factor increasing signal noise was the 100 MHz oscillator chip used as the data acquisition trigger. When the oscillator was powered, signal noise increased significantly. This increase in noise affected the reception of radio stations in the 100 MHz region. These radio stations were blocked out for approximately a 25 foot radius around the chip.

The 13 MHz signal contained amplitude modulation potentially reducing its ability to predict moisture content. The regression line for this frequency increased at Stardell Farms and decreased at Madison. Was this due to the difference in sensor plate separation distances or because of the moisture content range being measured?

An idea to potentially increase moisture prediction accuracy is to utilize frequencies which produce various regression line slopes? Another idea worth consideration is harmonic frequency information. Can multiple frequency information be acquired while driving only one frequency? Lastly, does the phase shift help moisture content prediction?

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APPENDIX A. SCHEMATICS AND PICTURES OF CIRCUIT BOARDS

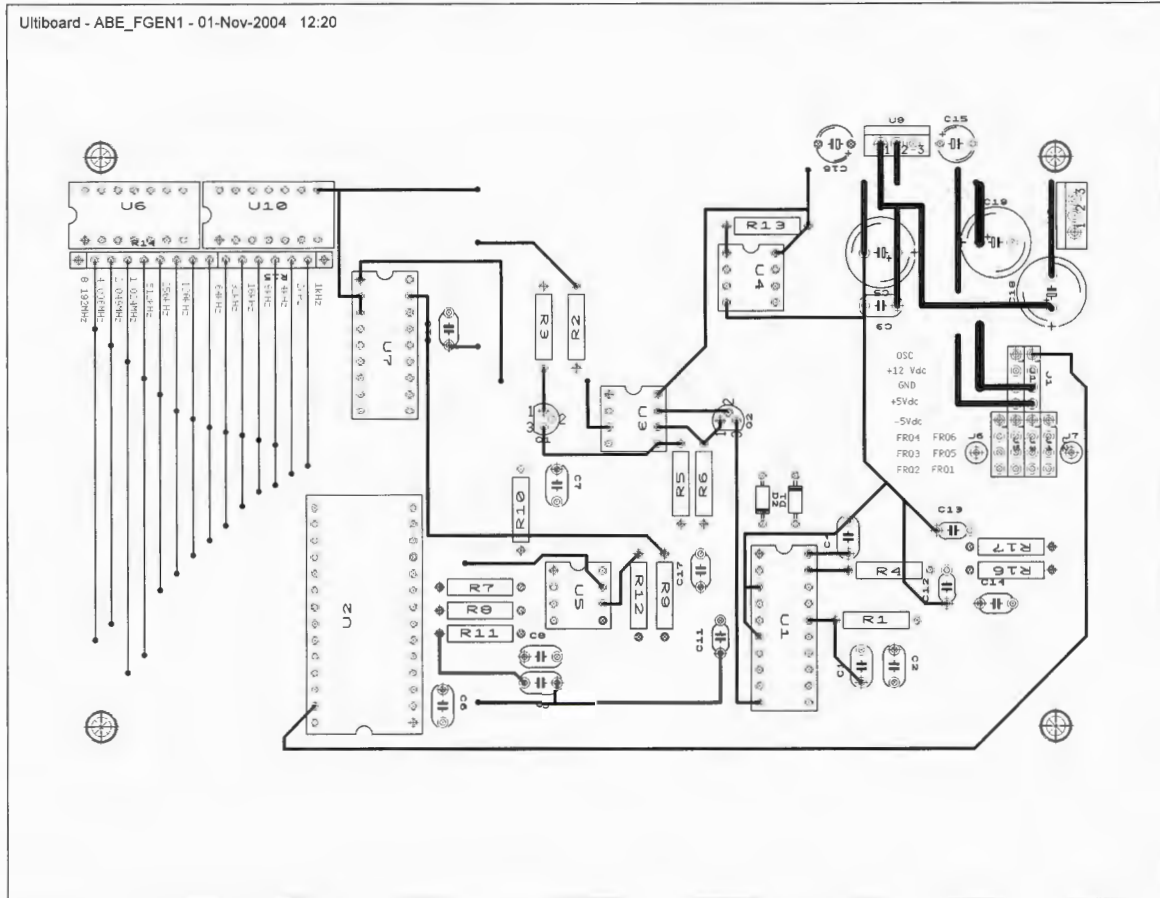


Figure A1. Copper top and silkscreen top of frequency generating boards

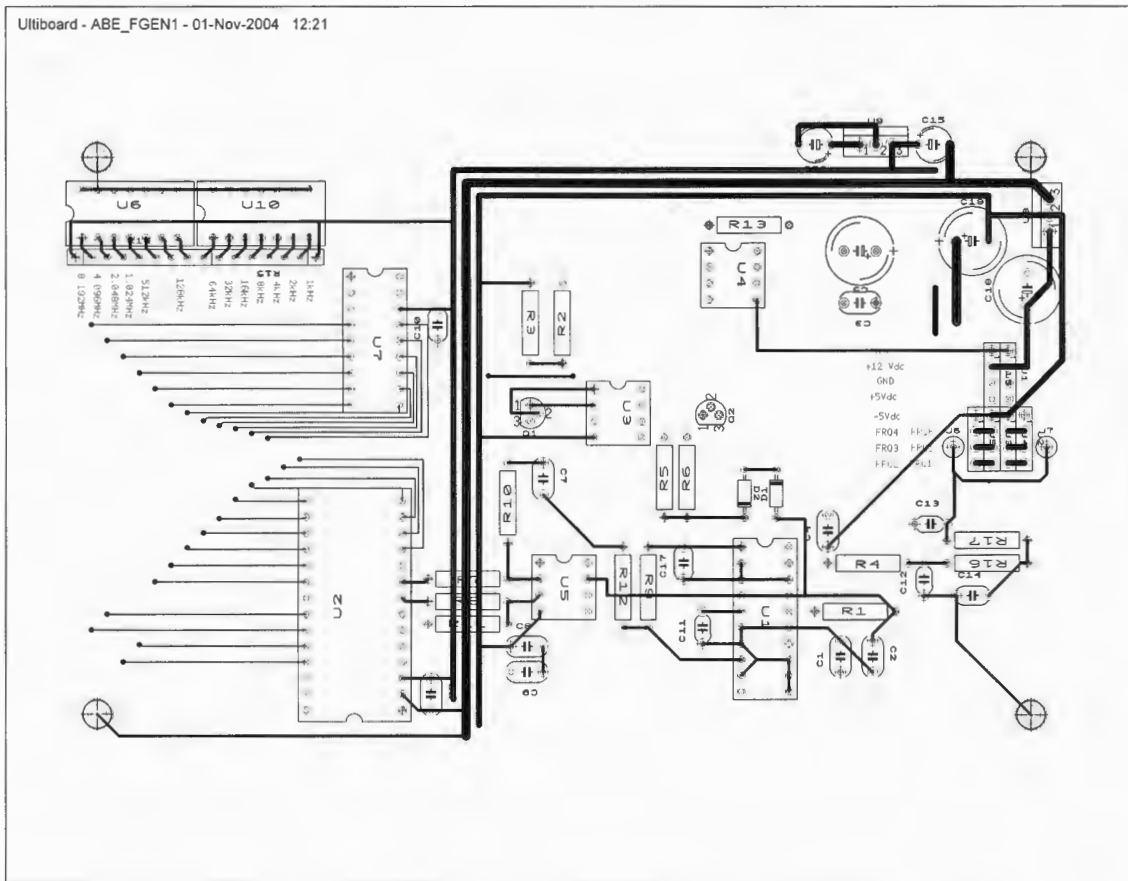


Figure A2. Copper bottom and silkscreen top of frequency generating board

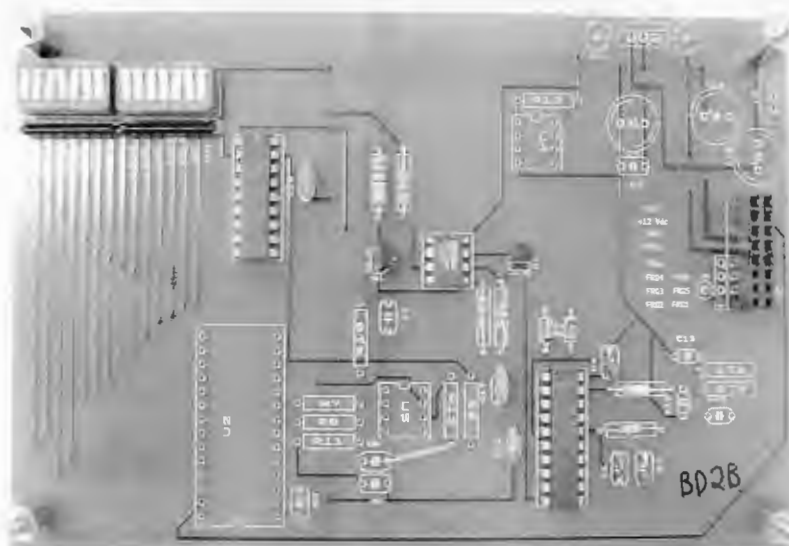


Figure A3. Top view of assembled frequency generating board

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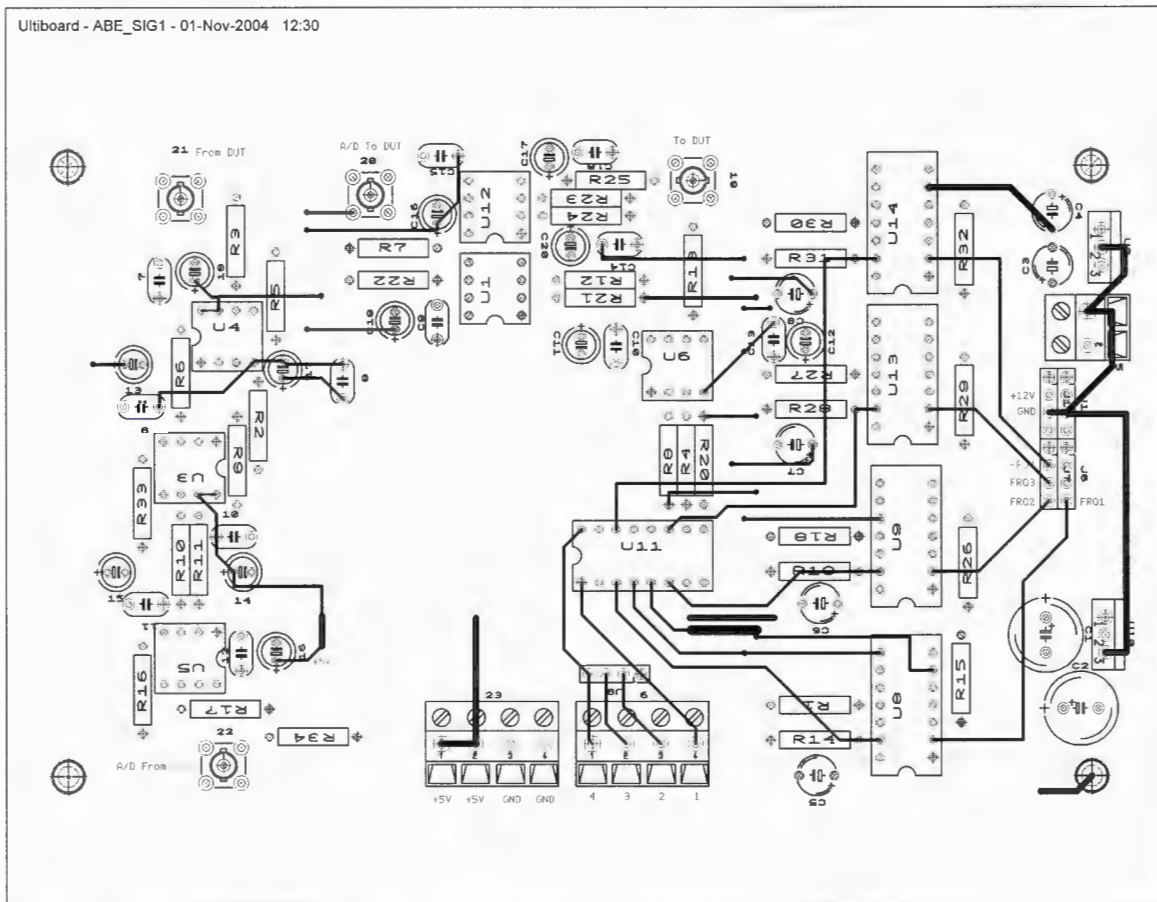


Figure A4. Copper top and silkscreen top of analog signal board

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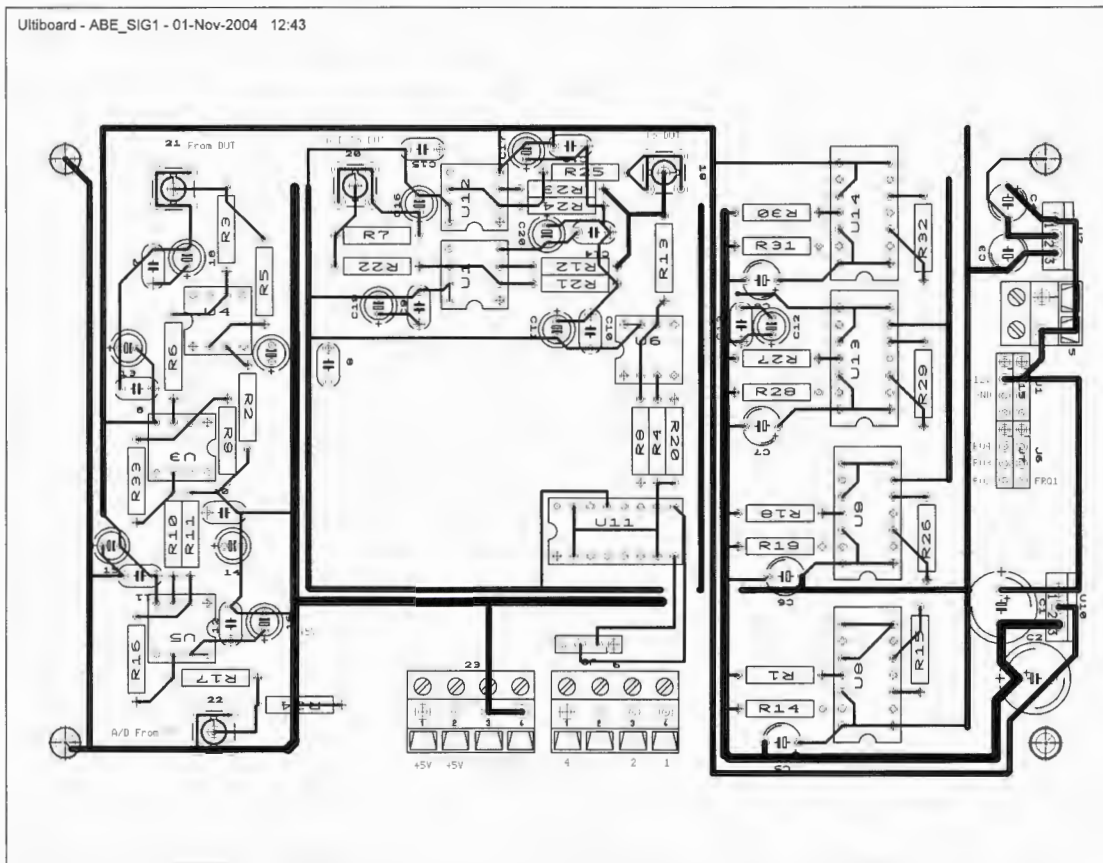


Figure A5. Copper bottom and silkscreen top of analog signal board

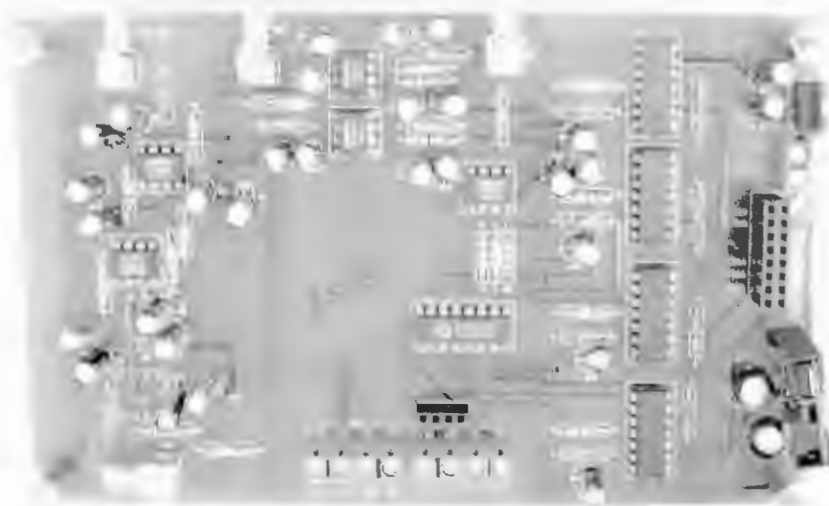


Figure A6. Top view of assembled analog signal board

APPENDIX B. DATA ACQUISITION SYSTEM



Figure B1. Circuit boards and data acquisition

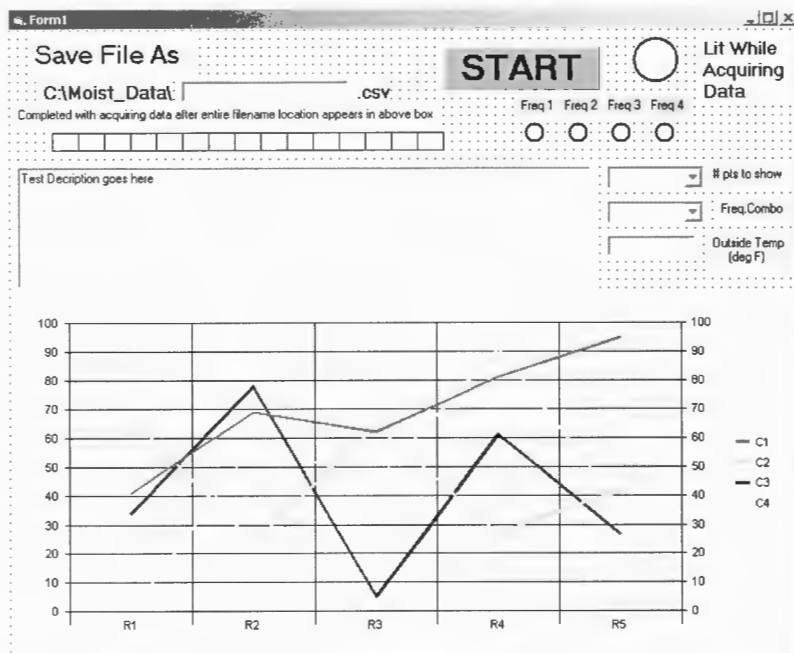


Figure B2. Visual basic form interface for data acquisition

APPENDIX C. SENSOR PLATE ASSEMBLY COMPONENT DRAWINGS

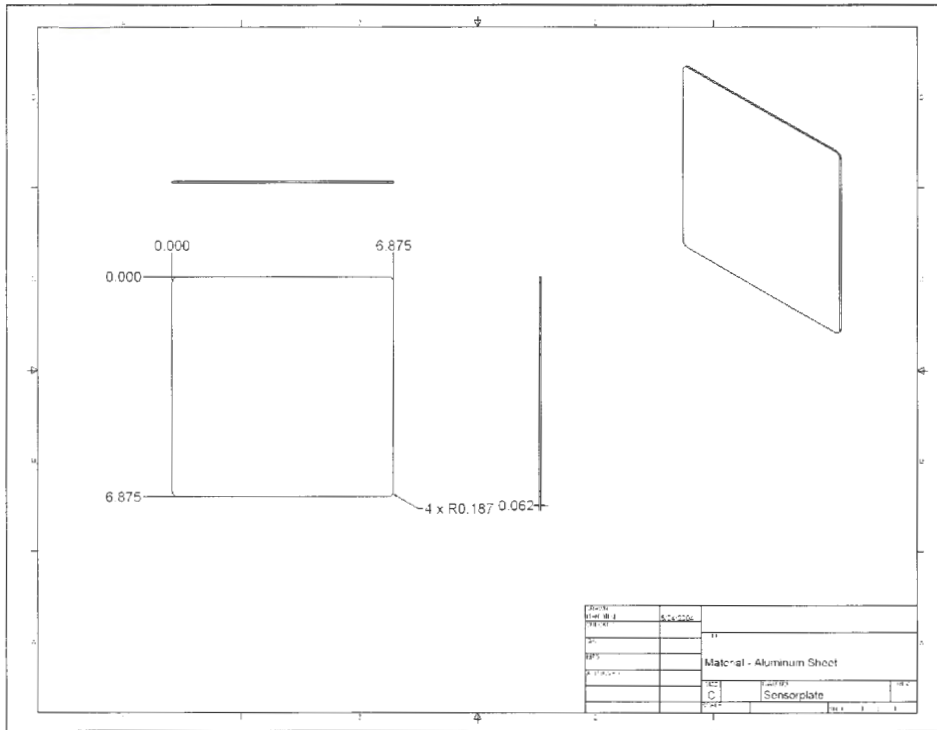


Figure C1. Sensor plate drawing

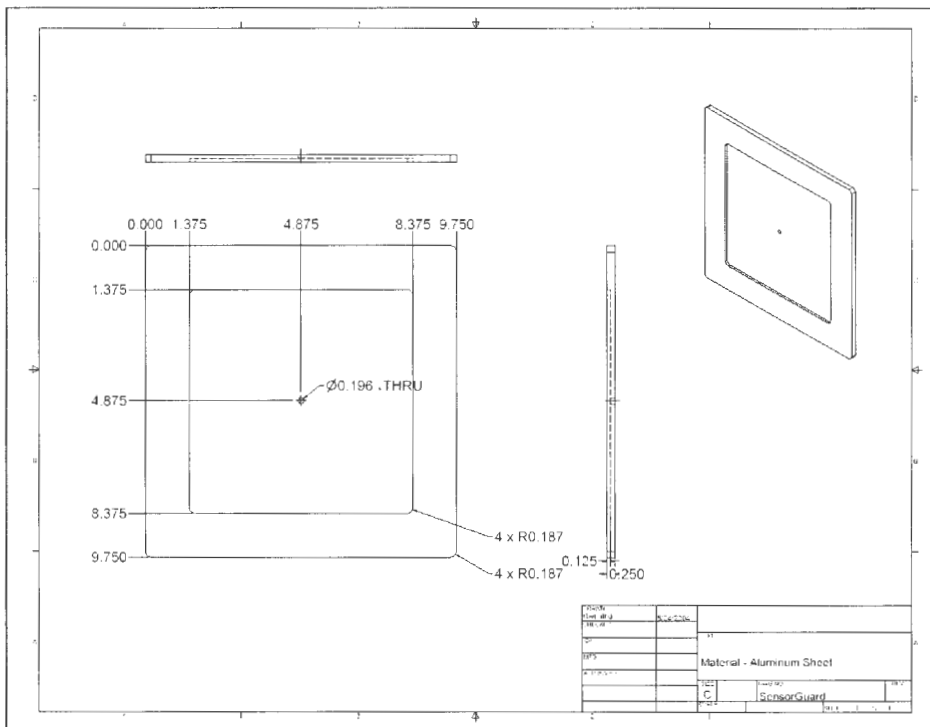


Figure C2. Guard plate drawing

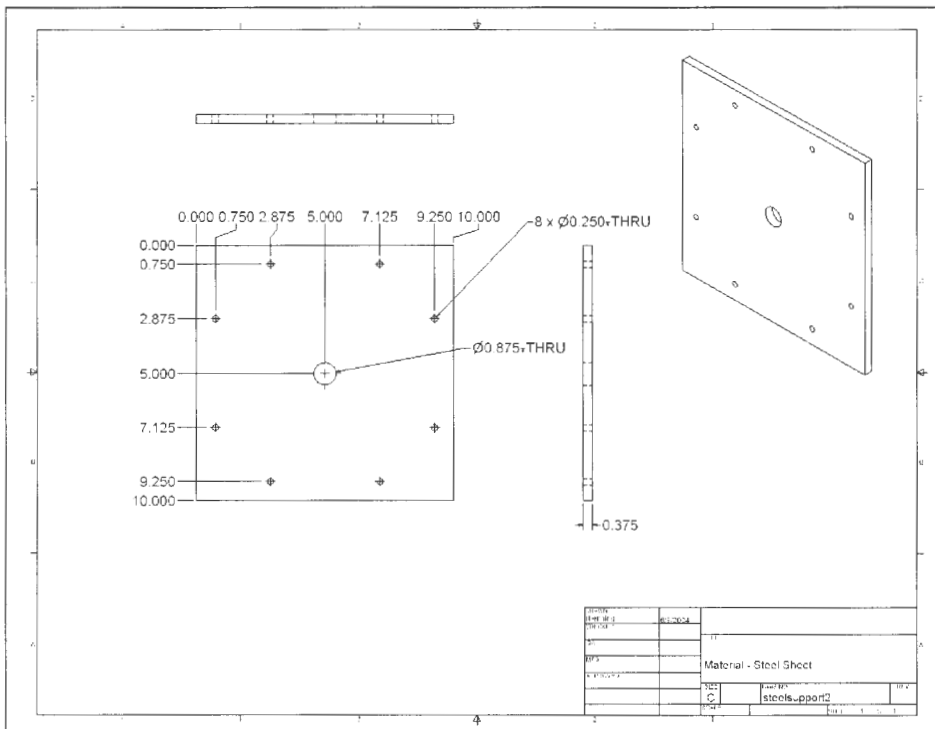


Figure C3. Rear sensor plate steel backing support drawing (closest to sensor plate)

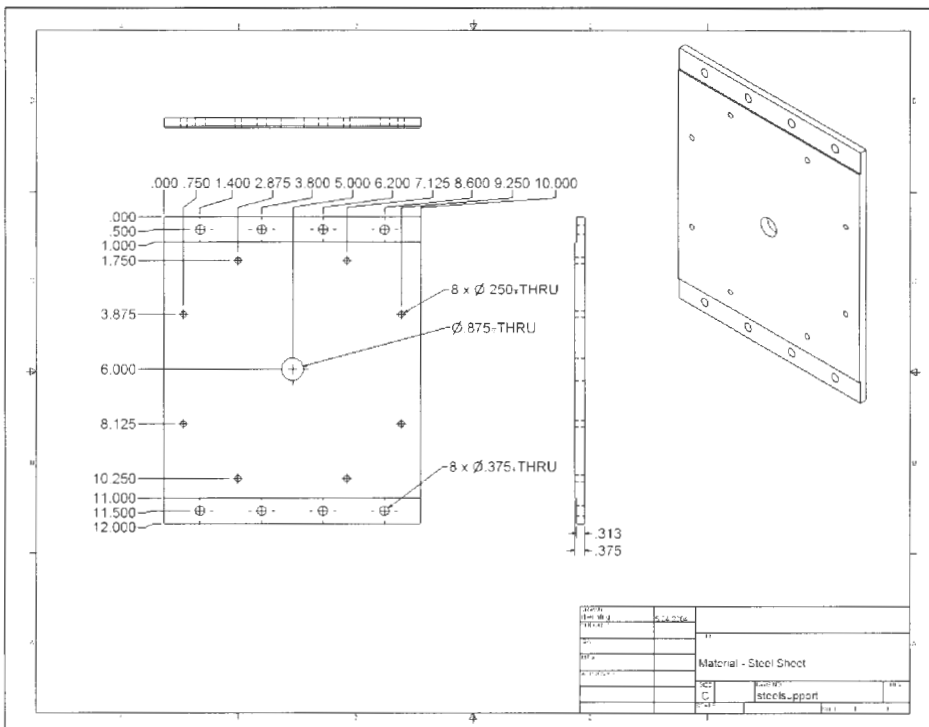
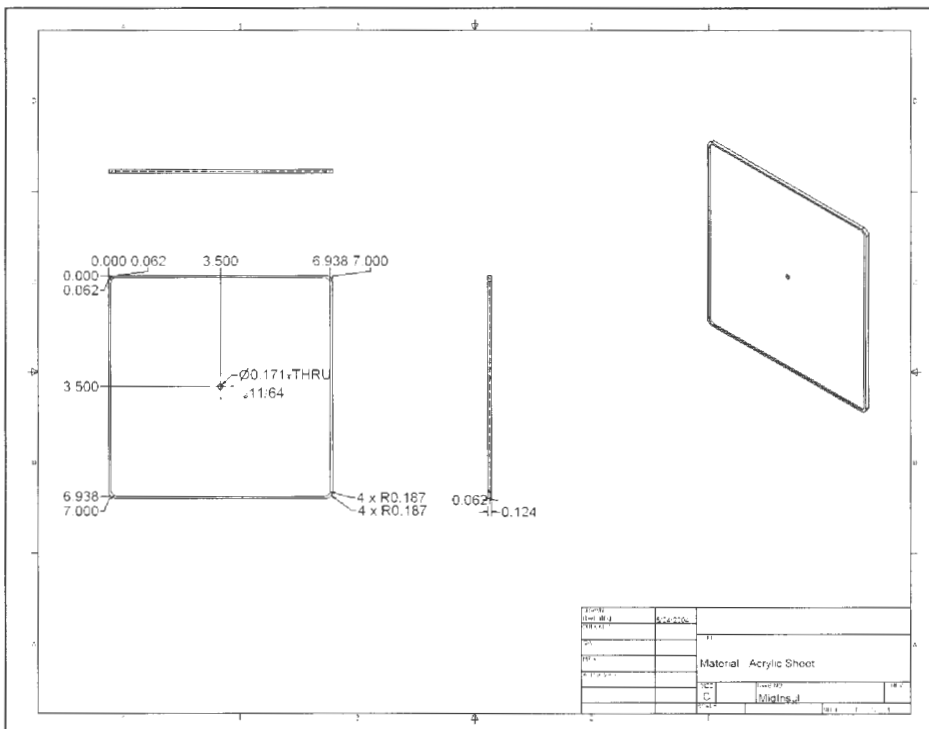


Figure C4. Rear sensor plate steel backing support drawing (fastens sensor plate assembly to mounting brackets)



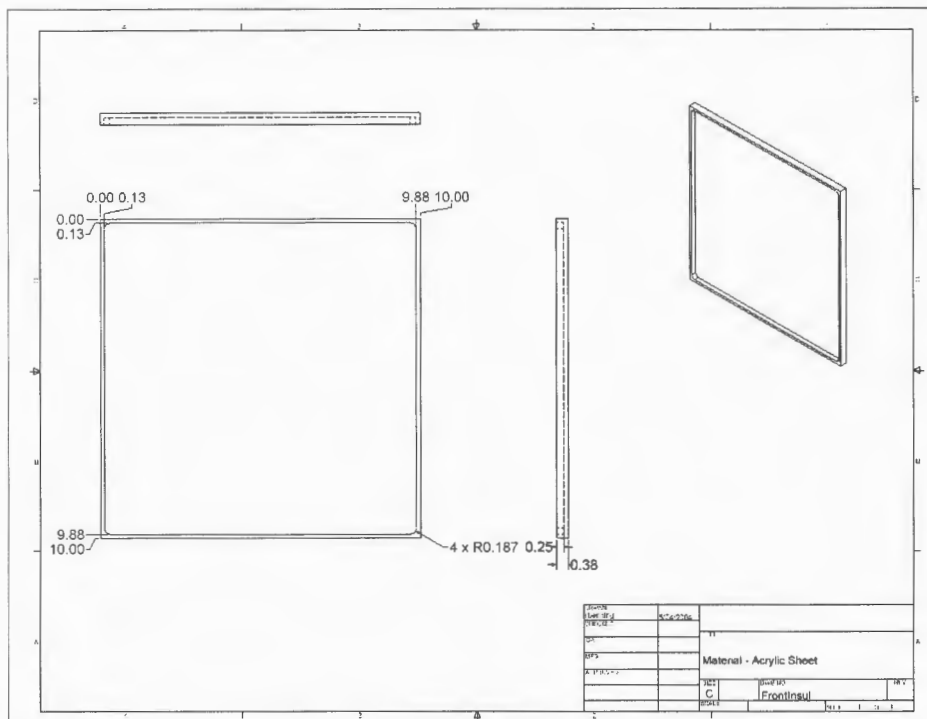


Figure C7. Front insulator plate



Figure C8. Sensor plate, middle insulator plate, guard plate, and back insulator plate

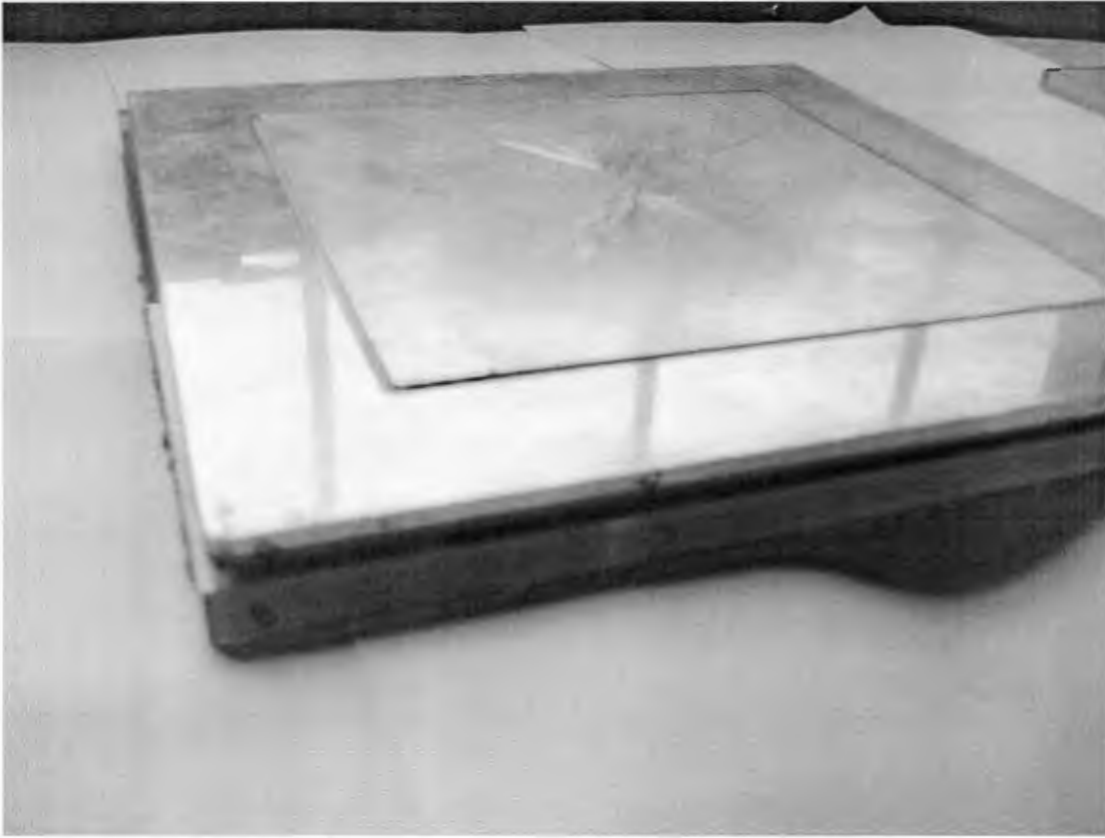


Figure C9. Back insulator plate, guard plate, middle insulator plate, and sensor plate assembled without front insulator plate

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